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THE TIN ORES OF UNCIA–LLALLAGUA, BOLIVIA.[1]

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INTRODUCTION.

THE town of Uncia lies at an elevation of 3,815 meters, about 100 km. southeast of Oruro, in the heart of the Bolivian Eastern Andes. Its latitude is 18° 27′ 58″ South and its longitude 60° 37′ 41″ west of Greenwich. The ore deposits are in the very center of the Bolivian metalliferous province. Toward the north and toward the south the intensity of mineralization gradually decreases. Uncia lies at the junction of the N.–S. axis of the Andes of Southern Bolivia and the NW.–SE. axis of the Andes of northern Bolivia, that is, Uncia lies at the bend in the range. The intensive opening up of the sedimentary shell at this bend is apparently the cause of the intrusion of unusually large quantities of igneous rock. It is the reason for the striking widening of the range and the numerous igneous intrusions in the Eastern Andes between latitudes 18° S. and 19° S. The bend in the axis of the range is also the cause of the abundance of ore deposits within this area—Oruro, Negro Pabellon, Morococala, Poopo, Avicaya, Antequera, Huanuni, Challapacheta, the Pujru-Vila Apacheta group, Colquechaca, and many others.

ROCK FORMATIONS.

Paleozoic, probably Devonian, unfossiliferous sandstones, quartzites and slates with NW.–SE. strike form an anticline west

[1] Translated from German manuscript by Joseph T. Singewald, Jr.

of Uncia in the crest of which the little stock [2] occurs that contains the world's largest tin ore deposit. Immediately east of Uncia a small mass of Cretaceous Puca sandstone is folded into the older sediments. In addition to the Uncia stock, volcanic rocks are represented by two small rhyo-andesite occurrences northeast of Uncia and extensive tuffaceous rhyolitic flows that extend from Negro Pabellon to a little west of Catavi. They are younger than the ore deposition.

Northeast of Uncia and at Catavi are hot springs. Lindgren has described the latter. They have deposited large sinter terraces consisting chiefly of aragonite, but include siliceous portions that contain opal and dark portions carrying manganese hydroxide gel with an appreciable WO_3 content. These springs are evidence of the very young—probably Pliocene—age of the ore deposition.

The Uncia igneous intrusion has the form of an ellipse with axes 2,000 m. long parallel to the strike of the range and 1,700 m. long at right angles thereto. The mine workings indicate it extends vertical in depth. It is a single intrusion. The rock is so deeply altered down to the lowest mine workings (775 m. below the surface) that it cannot be classified with certainty. Feldspars are completely decomposed and are only recognizable through their outlines. Biotite has altered to aggregates of minute sericite scales. Only the frequently crushed dihexahedral quartzes are unchanged. I am indebted to Dr. Brendler of Hamburg for an analysis of a specimen from the Siglo XX level. It is compared

[2] Throughout the manuscript the author uses the term "Lakkolith" for the Uncia intrusion and other similar bodies of igneous rock in the Bolivian Andes. These intrusions do not conform to the generally accepted shape and geologic relations of a laccolith. On questioning the author on this point he suggested using Steinmann's term "stehende Lakkolith," and showed by a sketch an intrusive mass suddenly tapering at the bottom into a small feeder such as usually shown in an ideal section of a laccolith. The main mass intrudes the strata and is not forced between them, and the vertical extent is much greater than the horizontal. A translation of the term "stehende Lakkolith" would give so misleading a concept to the English reader that it appears to me better to use the word "stock," the reader keeping in mind that the stock is believed by the author to diminish in cross-section quite abruptly in depth and not maintain or even increase its diameter with increasing depth. In support of this idea the author states that the mine workings at Potosi have clearly demonstrated such a shape for that intrusion.—J. T. S. Jr.

below with an analysis of a fresh dacite from Oruro given by Kittl.[3]

	Llallagua (Brendler)		Oruro (Kittl)	
	Analysis	Molecular Per Cent	Analysis	Molecular Per Cent
SiO_2	67.75	75.367	64.73	73.422
TiO_2	0.24	0.201	——	——
Al_2O_3	18.45	12.108	14.04	9.397
Fe_2O_3	0.95	0.395	0.63	0.2665
FeO	2.04	1.911	2.33	2.148
CaO	0.84	1.006	4.03	4.911
MgO	1.39	2.311	1.52	2.578
K_2O	5.67	4.038	2.43	1.765
Na_2O	2.46	2.663	4.63	5.109
P_2O_5	——	——	0.54	0.259
MnO	——	——	0.08	0.075
$-H_2O$	0.32		0.31	
$+H_2O$	——		3.53	

For the Oruro rock the values of A, C, and F after Osann are:

A (alkali feldspar) ..... 6.874 mols.
C (lime feldspar) ..... 4.911 "
F (dark constituents) ..... 4.992 "

According to the terminology of Osann the rock is a dacite.

Because of its great alteration the Llallagua rock can not be definitely determined. It differs from the Oruro rock especially in its lower lime content. On this basis it would have to be classed with the quartz porphyries. Alteration, however, commonly results in a decrease in lime and an increase in alumina.[4] It is very likely, therefore, that the fresh Llallagua rock is richer in lime and similar to the dacite of Oruro and other Bolivian localities.

The Llallagua rock has been altered not only through weathering but also by pneumatolysis. Pneumatolytic alteration—evidenced by the occurrence of tourmaline—is restricted to certain portions, especially to the vicinity of the veins and country rock

[3] Erwin Kittl, "Analisis de Rocas eruptivas de Bolivia," *Revista Minera de Bolivia*, 1927, Año 2, p. 51.

[4] Waldemar Lindgren, "Replacement in the Tin-bearing Veins of Caracoles, Bolivia," ECON. GEOL., vol. 21, p. 142, 1926.

inclusions. Such rock has a dark color caused by minute microscopic tourmaline needles. The pneumatolytic alteration is so complete in places that almost nothing is left of the original rock. Thin sections show much secondary quartz and pseudomorphs after mica and hornblende.

Although the rock often has a tuffaceous appearance in thin section, physical-chemical considerations such as the high temperature of ore formation lead me to the conclusion that the intrusion is not a neck but a stock which had a thin sedimentary shell. That no tuffs or glasses have been found points to the same conclusion.

The contact action of the magma on the intruded rock varies greatly at the different exposures but is generally slight. On the 600 m. level at Uncia, the country rock of the eastern contact is changed to a hard hornfels, indicating that the intensity of the contact action increases with depth. The condensation of the gases and solutions that carried the ores took place mainly within the stock. Only a few veins, the contact vein for example, extend for a short distance into the country rock. This is due to the great absorptive capacity of the porous quartz porphyry for the solutions. They condensed mainly near the apex of the intrusion.

THE VEINS.

There are two types of veins. One type are fillings of true faults with occasionally considerable displacement. They are persistent and regular in strike and dip. To this group belongs the important San Fermin-San José vein (Fig. 1) which lies near the west contact and dips to the east. It is the real "trunk vein" and is joined in depth by a number of smaller veins. Other are Forastera, Contacto, Reggis-Inka, and Salvadora. They are up to 1 m. in width, and the San Fermin locally, even 8 m. They have well-defined walls and commonly a drusy and brecciated filling. The strike ranges between N. 30° E. and N. 50° E.

Between the veins of the preceding type are countless smaller veins representing replacement of the wall rock along minute fractures. They are generally parallel to the large veins, but

some strike at right angles to them (cruzeras). They are of limited extent along the strike and are characterized by irregularity and non-persistence in their ore content. Their usual width is 5 to 30 cm. They become leaner in depth. The filling is compact and druses are rare.

A characteristic phenomenon is that some of the large veins do

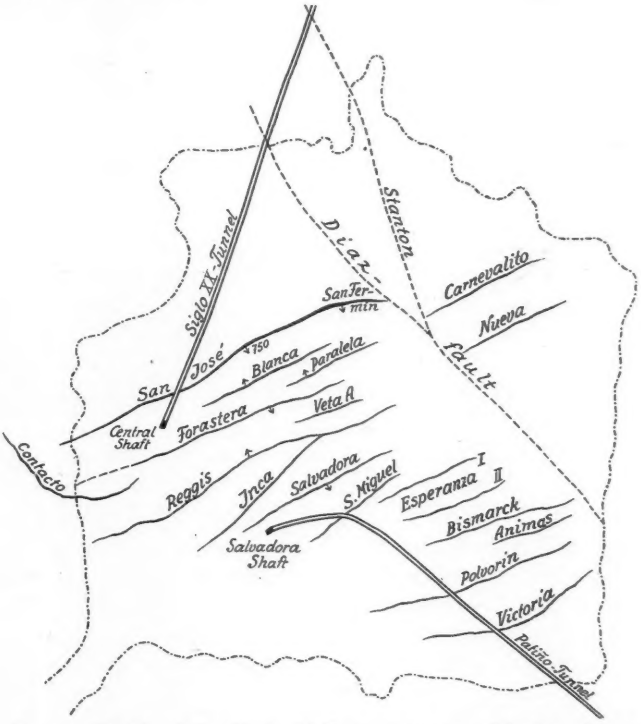

FIG. 1. Sketch of the Uncia Llallagua intrusion with the veins and faults. The broken line is the boundary of the stock on the surface.

not extend to the surface. An explanation of this will be suggested further on. In Uncia-Llallagua 9 main veins and about 30 small veins have been worked (Fig. 1).

Major tectonic movements occurred within the stock subsequent to ore deposition. The northeastern portion with the veins Carnevalito and Nueva sank along the Stanton and Diaz faults The faults are barren of ore and filled only with clayey comminuted material.

PARAGENESIS OF MINERALS.

The mineral filling all the veins is quite similar despite many variations. The following minerals were recognized which are described in paragenetic sequence (from near magmatic to more remote magmatic affiliations:

Hypogene Minerals.

Tourmaline.—Abundant in the country rock of the veins and in certain barren shear zones. Occurs irregularly distributed in quartz in small microscopic needles and shows weak pleochroism (Fig. 2).[5] Almost never absent when cassiterite occurs, but decreases in quantity upwards. The greisen accompanying the San Fermin vein on the deepest level of the mine (775 m. below the surface) consists only of tourmaline, quartz, and a little cassiterite. Mica and topaz are absent. In part the tourmaline resembles achroite and is without pleochroism.

Quartz.—Associated with the tourmaline is much fine-grained quartz as a pneumatolytic alteration of the country rock. Because of this the silica content of some of the rock is very high.

The frequently well-developed trapezohedral crystals accompanying cassiterite in druses are high-temperature quartz formed under 560°. It is contemporaneous with the cassiterite or older.

The abundant chalcedony is probably supergene.

Cassiterite.—Occurs almost exclusively in twins of the Zinnwald type. They rarely attain to a size of 1 cm., and are generally much smaller. Transparent crystals are rare; they are commonly black. An analysis by G. Greene[6] of a cassiterite crystal yielded 94.06 per cent SnO_2 and 4.30 per cent Fe. The

[5] The microphotographs of this paper were made with the kind aid of Mr. Ehrenberg.

[6] G. Greene, "Solubility of Tin Minerals," *Eng. and Min. Jour.*, vol. 122, p. 417, 1926.

crystals are made up of zonal layers of various degrees of color intensity. The most abundant form of twin is after (101), and is usually in polysynthetic-cyclic aggregates. In brecciated veins, especially in the San Fermin and Salvadora, cassiterite crystals

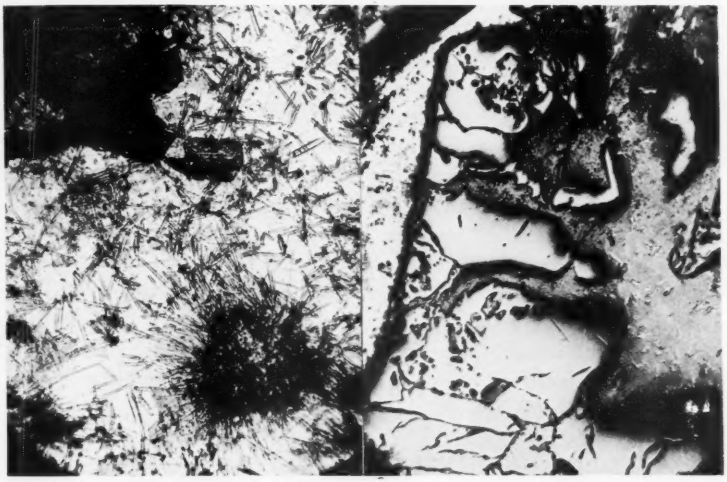

FIG. 2. FIG. 3.

FIG. 2. Tourmaline-greisen, country rock. San Fermin vein, Siglo XX level. Thin section, ×74.

FIG. 3. Cassiterite crystal (high relief) surrounded by stannite with unmixing particles of chalcopyrite. The cassiterite crystal is strongly corroded. San Fermin vein, 330 m. below surface. Polished section, ×47.

fill cavities between quartz crystals and coat country rock fragments.

In the large ore shoots, as those of the San Fermin vein, cassiterite is the principal constituent of the ore and often occurs associated with wolframite, bismuthinite, and pyrrhotite, less frequently with stannite and apatite, without gangue minerals.

In one of my specimens from the 60 m. level of the Salvadora shaft, in addition to the usual twinned cassiterite, are spherical aggregates of faintly colored needles. Winkelmann describes

cassiterite with gel structure in rhyolite from Uncia. It would appear that cassiterite presumably formed from sols is more abundant near the surface. I have not observed such in the deeper portions of the deposit.

Arsenopyrite.—Occurs isolated in depth, as in the deepest level of the San Fermin, in veinlets in greisen, apparently of pneumatolytic origin. Since it does not occur in association with other minerals, its genetic position can not be definitely determined.

Wolframite.—Wolframite of normal composition frequently accompanies cassiterite, especially on the Uncia side. Occasionally its crystals are covered by cassiterite crystals. Manganese-rich varieties (hübnerite) are formed under hydrothermal conditions.

Bismuthinite.—Commonly accompanies the cassiterite, especially in the Llallagua section, where it is found in nearly all veins. Its lancet-like crystals, attaining a length of 10 cm., never show free terminations but are always embedded in cassiterite or pyrrhotite. Occasionally its crystals are coated with cassiterite. In some veins the bismuthinite content varies proportionally with that of cassiterite.

Acicular bismuthinite, similar to jamesonite, was seen in druses in arsenopyrite.

Native Bismuth.—Occasionally abundant and in masses weighing up to several kilograms (San Fermin vein). It is never in crystal form, but together with bismuthinite constitutes the filling between quartz crystals. Since it occurs to a depth of 400 m., I do not agree with Kittl [7] in ascribing its formation from bismuthinite through a process of reduction in the zone of oxidation. I believe that it was deposited directly from solutions under pneumatolytic conditions and that the predominance of native bismuch near the surface and of bismuthinite in depth, as frequently observed in Bolivia, is a phenomenon of primary difference in depth.

Pyrrhotite is the most important mineral associated with cassiterite in most of the veins. It forms massive compact masses in which cassiterite, bismuthinite and wolframite are embedded

[7] Kittl, "Algunas observaciones sobre la formation de Bismuto nativo," *Rev. Minera, Soc. Argentina de Min. y Geol.* Año 2, 1930, pp. 1–3.

frequently with idiomorphic boundaries. The abundance of pyrrhotite has escaped the attention of most observers because it has been almost entirely converted to pyrite and marcasite. Only occasionally, especially within the sediments, does one encounter fresh remnants or remnants in process of alteration.

Apatite is the only hypogene phosphate that occurs in appreciable quantity, even though mainly microscopic. It is confined to a few veins (San Fermin). Occasionally it is found in druses as rose-colored tabular crystals, but its usual mode of occurrence is in blue-green masses intergrown with cassiterite and pyrrhotite. It is of pneumatolytic origin.

Monazite.—This is also a pneumatolytic mineral which was found once on the 60 m. level of the Salvadora vein as small, light rose-colored crystals intergrown with cassiterite and nacrite.

Stannite.—Stannite is more common than generally recognized but is confined to certain veins. As a mineral of the high-temperature hydrothermal phase, it is more abundant nearer the surface. According to the former superintendent of the Uncia Mine, Engineer Hans Block, some parallel stringers of the Salvadora vein consisted almost solely of stannite. The mineral was found in such quantity near the surface at Uncia that the erection of a silver leaching plant was seriously considered in 1905. The mineral is especially abundant microscopically in the ores of the Polvorin and San Fermin veins. In the latter vein it is in part at least older than bismuthinite but always younger than cassiterite, the strongly corroded crystals of which it encloses (Fig. 3). It includes unmixing particles of chalcopyrite. The embedding of cassiterite crystals in stannite, which is so frequently seen in Bolivian ores, can be explained in two ways. On the one hand, stannite may belong to a later phase of ore deposition and may have been deposited by alkaline solutions that dissolved cassiterite. On the other hand, it may have been deposited by the same solutions that precipitated cassiterite, bismuthinite, and pyrrhotite, and its deposition accompanied by resorption of the previously precipitated cassiterite. On the basis of my observations on other deposits, I am more inclined to hold to the latter explanation.

The stannite usually occurs massive. However, on the 120 m.

level of the Salvadora vein, magnificent twinned crystals up to 4 cm. in size were encountered on crystals of cassiterite and covered with crystals of hübnerite.

In depth, below 400 m., stannite disappears completely.

Sphalerite appears to be limited to the upper portion of the deposits as a hydrothermal mineral. No material was available to me for investigation. The sphalerite is said to be rich in cadmium and to have been found in the Contacto vein together with franckeite.

Franckeite.—This mineral was not determined analytically, but in polished surfaces by comparison with franckeite from Huanuni. It occurs as a very thin coating and in tabular crystals on pyrite derived from pyrrhotite. It was not seen with fresh pyrrhotite. At a depth of about 300 m. on the Contacto vein, I observed a 4 cm. stringer with cassiterite on both walls and franckeite, pyrite derived from pyrrhotite, and siderite in the middle. A polished section showed cassiterite filling the spaces between the franckeite crystals. This may represent contemporaneous deposition of franckeite and cassiterite. At greater depths franckeite was not observed.

Hübnerite.—It occurs near the surface in separate veinlets of more remote magmatic affiliation. It possesses the typical brown color and radiating prismatic structure. Excellent crystals are found in druses. In the Contacto vein it is associated with cassiterite. In a specimen from the Salvadora vein cassiterite crystals encrust hübnerite crystals, that is, are younger than the hübnerite.

Siderite.—Occurs sparingly with pyrrhotite.

Pyrite.—Appears to play a subordinate role as a hypogene mineral. Occasional it coats cassiterite. Most of the pyrite has been derived from pyrrhotite.

Rare hypogene minerals are chalcopyrite and galena.

Supergene Minerals.

Since the oxidation zone has long since been worked out, I was unable to study the minerals in place but was dependent on specimens from older collections. At the outcrop of most veins were

large quantities of cavernous limonite derived from pyrrhotite. Davy mentions native arsenic and realgar derived from arsenopyrite. Greenockite as a yellow, pulverulent coating on pyrite is said to have been quite common, especially in the San Fermin vein.

Concerning supergene bismuth minerals, I observed bismuth ochre in cassiterite pseudomorphic after bismuthinite. Among the specimens of bismuthinite from the upper levels were some with a weaker metallic lustre. On polished sections it was seen that the broad crystals of bismuthinite were opening up into leaves along cleavage planes and were bent into ice crystal and feathery forms. They possessed a darker color than the fresh bismuthinite and lower hardness. The mineral is an oxysulphide of bismuth and apparently identical with karelinite, Bi_4SO_3 (Fig. 4). A separation of this mineral for analysis is impossible on account of its intimate intergrowth with bismuthinite. The mineral must have been quite abundant in the upper levels at Llallagua

With a limited supply of oxygen, stannite decomposed to chalcopyrite, chalcocite, bornite and covellite. In the presence of more abundant oxygen the latter minerals were oxidized. Copper sulphate migrated downward, reacted with fresh sulphides and gave rise to copper-rich cementation zones with native copper. The tin content of the stannite in the form of metastannic acid appears not to have migrated, but to have been deposited *in situ* as cassiterite. In the specimens of stannite from near the surface that were available to me, I could find no supergene cassiterite. Such may have been present, but overlooked in mining. Koeberlin[8] states that large quantities of stannite were oxidized in the San Fermin vein. He describes beneath the limonitic zone a 10 m. thick zone of rich cassiterite, marcasite, and chalcanthite. The latter, in the almost complete absence of other copper minerals, must have originated from the weathering of stannite.

The phosphorus content of the primary ores and the ready solubility of the apatite gave rise to the formation of numerous and in places large quantities of supergene iron and aluminum

[8] Koeberlin, "Geologic Features of Bolivia's Tin-bearing Veins," *Eng. and Min. Jour. Press*, vol. 121, pp. 636–642, 1926.

FIG. 4. Bismuthinite (white) altering to karelinite (gray). The black is bismuth ochre and limonite. Salvadora vein. Polished section, × 235.

FIG. 5. Pyrite pseudomorphic after pyrrhotite with basal cleavage (white) and wolframite (gray). San Fermin vein. Polished section, × 12.

FIG. 6. Pyrrhotite altering to pyrite. San Fermin vein. Polished section, × 12.

phosphates. In the San Fermin vein, 400 m. beneath the surface, I observed cavernous masses of wavellite that in places filled the entire width of the vein. Wavellite is the most common of the phosphates and occurs very frequently as a coating on quartz crystals and cassiterite and as pseudomorphs after large tabular marcasite crystals. In the wavellite druses are occasionally the iron-aluminum phosphates described by Gordon, vauxite (light blue), metavauxite, and paravauxite (both colorless). Vivianite, which is especially characteristic of the Bolivian deposits, occurs in beautiful transparent crystals both in druses in massive cassiterite and together with phosphate-allophane and pyrite in separate veins. The abundant occurrence of vivianite ceases at about 360 m. below the surface. Several of the phosphates that I observed have not yet been named, as, for example, a hydrous iron phosphate that together with vauxite forms white silky tufts. On heating it turns brown.

In open fractures that cut the Forastera vein, I observed at a depth of 450 m. besides wavellite an abundance of chalcedony, in the outer layers of which minute quantities of sulphides are visible in polished sections. They include pyrite, wurtzite, a white isotropic ore of the smaltite family, a light green mineral intergrown with the white that is perhaps tetrahedrite, and an unknown anistropic rose-colored copper mineral. These chalcedony deposits may have been formed by either ascending or descending solutions.

Before leaving the consideration of the minerals, the pyrite and marcasite derived from pyrrhotite should be mentioned. They are widespread and abundant in nearly all the veins. Pseudomorphs of pyrite after pyrrhotite are found in all the Bolivian deposits. Polished sections show that the transformation begins along the boundaries of pyrrhotite with other minerals and advances into the pyrrhotite individuals to form a network of pyrite laths enclosing fresh pyrrhotite grains (Fig. 6). Even when the transformation is complete, the basal parting of the pyrrhotite is well preserved (Fig. 5). A subtraction of substance appears to accompany the change, because countless druses are left lined with minute pyrite crystals. To explain the chemistry of this trans-

formation is difficult. Either a subtraction of iron or an addition of sulphur may have occurred. A subtraction of iron (as sulphate or carbonate, is an oxidation process confined to the zone of oxidation. In Llallagua almost all pyrrhotite is transformed to pyrite, even at depths to which oxidation processes do not reach. Fresh pyrrhotite occurs only in small nests. Even at depths of 400 m. or as much as 600 m. there is little or no pyrrhotite. In other Bolivian deposits, however, as at Tasna, there is much pyrrhotite at depth; there the transformation does not seem to have extended deep. Similar observations are at hand for other deposits from other parts of the world. A subtraction of iron can have occurred only as a double transformation (perhaps through the formation of acid iron carbonate). Newly formed carbonates or hydroxides ought then to occur in association with the pyrite. But such is not the case. At Llallagua even the readily oxidizable bismuthinite within the pyrite pseudomorphs is preserved unaltered. Another explanation must therefore be sought. The change must have been brought about through a direct addition of sulphur molecules. This could take place through the action on the pyrrhotite of thermal waters carrying H_2S according to the reaction:

$$FeS + H_2S = FeS_2 + H_2.$$

It is reasonable to assume some solution and transportation of pyrrhotite at the same time. The formation of pyrite from pyrrhotite would not then be a process restricted to the zone of oxidation but would be restricted to the action of thermal waters containing hydrogen sulphide. The process requires further elucidation.

Summary of Hypogene Mineralization.

The following general statements can be made concerning the distribution and quantity of the hypogene minerals in the Llallagua-Uncia deposits.

1. In large quantity: pyrite and marcasite derived from pyrrhotite.
2. In quantity: tourmaline, quartz, cassiterite.
3. In appreciable quantity: bismuthinite, wolframite, stannite.

4. Sparingly: arsenopyrite, native bismuth, pyrite, franckeite, hübnerite, sphalerite(?).
5. Sporadically or in minute quantity: apatite, monazite, siderite, nacrite, chalcopyrite.

ORIGIN OF THE ORES.

The sequence of minerals in the Uncia-Llallagua deposit corresponds to the order that has been worked out for the magmatic cycle from physical-chemical considerations. Three zones are recognized in ascending order, each one characterized by the predominance of different minerals. In the deepest portions of the deposit tourmaline is most abundant. It is not confined to the immediate wall rock of the veins, but is widely and irregularly distributed through the country rock. Higher up it is more restricted in its distribution and disappears entirely near the surface.

The second zone is characterized by an abundance of heavy metals. Cassiterite appears first. It is found in small quantity as a constituent of the greisen in the deepest mine workings (in the San Fermin vein at 775 m. below the surface). The lower boundary of tin ore deposition in the Uncia section lies between 550 m. and 600 m. below the surface; in the Llallagua section, which is nearer the periphery of the intrusion, it lies deeper. Arsenopyrite is the oldest of the sulphides. The formation of tourmaline ceased when the deposition of cassiterite was initiated. It occurs in the wall rock of the tin veins as an older deposition, but not within the compact cassiterite masses characteristic of the second zone. As a consequence of rapidly falling temperature, cassiterite was deposited very suddenly. It occurs in the form of shoots (*bolsones*) of unexampled richness but of very limited vertical extent. These shoots are found at greater depths near the periphery of the stock on the San Fermin vein, as a consequence of the more rapid cooling under the influence of the proximity of the intruded rock, than in the center, as for example in the Salvadora vein, where they extend close to the present surface. Together with cassiterite were deposited bismuthinite, wolframite, apatite, and pyrrhotite. Quartz continued to be deposited in con-

siderable quantities. The nature of the mineralization suggests very concentrated acid solutions with strong gas phase and temperature of 400° to 500°. The wall rock of the ore shoots contains tourmaline but has also been intensively sericitized.

The third zone, farthest removed from the magma, is characterized by less cassiterite and the predominance of sulphides and sulphosalts of tin, lead, copper, antimony, and zinc. These are lacking in the lower parts of the mine at depths below 450 m., and increase in abundance upwards. Stannite appears first and even occurs in the rich cassiterite shoots. Then follow in order franckeite, hübnerite, sphalerite, siderite, all minerals of the hydrothermal sequence. Their investigation is made difficult because the uppermost part of the deposit has been leached by oxidation processes. Furthermore, the upper parts of the mine are worked out and no longer accessible. Koeberlin's statement that a number of the most important veins do not extend to the surface is perhaps to be explained by the fact that in their uppermost parts they did not carry cassiterite but easily destroyed sulphides and sulphosalts and that only limonite remains.

The transformation of pyrrhotite into pyrite and marcasite doubtless occurred at the close of the period of mineralization.

CONCLUSIONS.

The formation of the Uncia-Llallagua deposit is considered to have been a single continuous process. Differences in mineral content are not regarded as due to deposition by different solutions ascending at different times, but by one and the same solution which changed its composition through fractional distillation and thereby gave rise to various primary differences in depth. This view can not be proven absolutely, but is probable from the standpoint of our understanding of the physical-chemical principles of ore deposition.

Let us summarize once more the results of the preceding considerations. High tension solutions rich in volatile constituents penetrated the top of a small stock, the tuff-like quartz porphyry of which was ideally suited for the deposition of ores. Mineral-

ization began with the formation of tourmaline greisen. The solutions, penetrating the countless fractures of the quartz porphyry, decreased in pressure so rapidly that the bulk of their heavy metal content was precipitated in a relatively small space. Precipitation began with little sulphide. With falling temperature the initially acid solutions became neutral and sulphosalts (stannite) were precipitated nearer the surface. Most of the heavy metal content had been deposited before the solutions reached the surface. To what extent ore deposits of the hydrothermal phase were deposited in the eroded crest of the stock and the former sedimentary cover we can not know. Analogy with other related deposits renders it likely that hydrothermal chalcopyrite-pyrite veins and argentiferous galena-sphalerite veins existed.

The deposit is a transition between the intrusive-pneumatolytic tin veins in northern Bolivia and the extrusive-hydrothermal ones in southern Bolivia. It is more closely related to the former, however, because of the prominence of tourmaline, cassiterite, and pyrrhotite, a characteristic assemblage of many of the northern deposits (*i.e.* Araca). On the other hand, in the northern deposits, the well-defined primary differences in depth that signify an unusually quick cooling of the solutions are lacking. Likewise they do not show the simultaneous deposition of minerals which under normal conditions are widely separated, as bismuthinite and stannite or cassiterite and franckeite.

Finally, attention should be called to the fact that the great enrichments that Koeberlin ascribed to secondary processes are satisfactorily accounted for in another way by the preceding explanation.

MARBURG, GERMANY.

OVERTHRUST FAULTING AND OIL PROSPECTS OF THE EASTERN FOOTHILLS OF ALBERTA BETWEEN THE BOW AND HIGHWOOD RIVERS.[1]

G. S. HUME.

INTRODUCTION.

THE Foothills occupy a belt of country 12 to 25 miles in width between the Rocky Mountains on the west and the Great Plains on the east. They extend from the International Boundary to north of Peace River and southward into northern Montana. They are composed of rocks ranging in age from Paleozoic to Tertiary, although the greater part of the outcrops consist of Cretaceous sandstones and shales. These have been strongly folded and faulted and have been eroded into a series of parallel northwest and southeast trending ridges and hills, across which at right angles to the strike the major lines of drainage have cut well-defined valleys. The ridges increase in elevation from about 4000 feet on the east to 6000 feet in front of the limestone escarpment which sharply defines the western limit of the Foothills belt and forms the front of the mountains. On their eastern edge the rounded ridges of the Foothills belt gradually give place to the undulating plains although structurally there is a distinct line of demarcation.

LOCAL STRUCTURAL FEATURES.

Character of Faulting.—The foothills are characterized by numerous nearly parallel reverse strike faults, often of great length and mostly of unusual steepness. This latter fact has been noted by Mackenzie[2] and others. In the area studied by the writer between the Highwood and Bow Rivers (Fig. 1) most of

[1] Published by permission of the Director, Geological Survey of Canada, Ottawa. Presented before the Society of Economic Geologists, Toronto Meeting, December 30, 1930.

[2] Mackenzie, J. D., *Trans. Royal Soc. Canada*, vol. 16, ser. 3, sec. 4, 1922.

the faults dip (westward) 65° to 75° or more at the surface. Consequently they outcrop in straight lines regardless of topography, in fact this is the main proof of steepness, although a few fault surfaces have been observed. The drilling of wells in Turner Valley (see Fig. 1) and in the so-called New Black

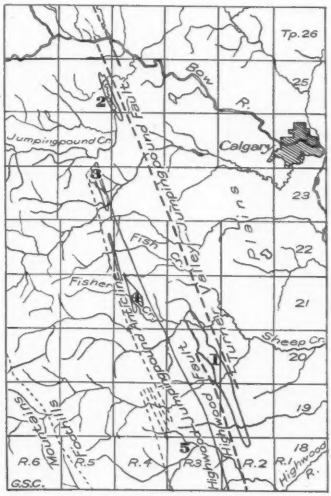

FIG. 1. Highwood-Bow River area, Alberta. (1) Turner Valley anticline, (2) Jumpingpound anticline, (3) Two Pine anticline, (4) Fisher Creek structure, (5) Highwood anticline.

Diamond structure, two miles west of Turner Valley, has indicated at least two faults which, although steep at the surface, become low-angle faults at depth with westerly dips of not more than 20°. One of these faults underlies Turner Valley and has been penetrated by at least four wells, two of which after passing through a considerable thickness of Paleozoic limestone, cut the fault and the Cretaceous strata beneath. The other fault underlies the New Black Diamond structure and has been cut by two wells. This part of the Foothills, therefore, consists of fault plates or nappes overlying one another, and the Foothills mass

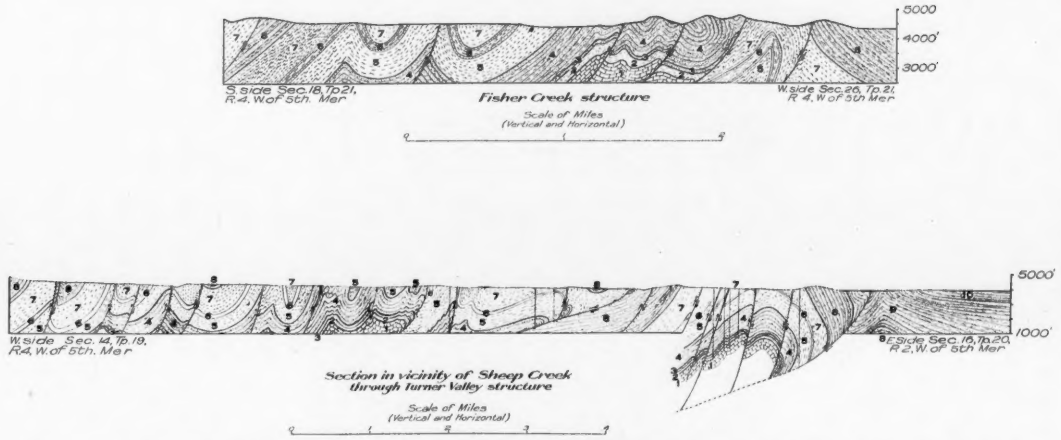
5000
4000'
3000'
S. side Sec. 18, Tp. 21, R. 4, W. of 5th. Mer.
Fisher Creek structure
W. side Sec. 26, Tp. 21, R. 4, W. of 5th Mer.
Scale of Miles
(Vertical and Horizontal)
5000'
1000'
W. side Sec. 14, Tp. 19, R. 4, W. of 5th. Mer.
E. side Sec. 15, Tp. 20, R. 2, W. of 5th Mer.
Section in vicinity of Sheep Creek through Turner Valley structure
Scale of Miles
(Vertical and Horizontal)

FIG. 2. 1. Paleozoic limestone. 2. Fernie (Jurassic) formation. 3. Kootenay (Lower Cretaceous) formation. 4. Blairmore (Lower Cretaceous) formation. 5. Lower Alberta shale (Colorado). 6. Cardium sandstone. 7. Upper Alberta shale (Colorado and Montana). 8. Belly River (Montana) formation. 9. Edmonton (Upper Cretaceous) formation. 10. Paskapoo (Eocene) formation.

is believed to have been thrust eastward onto the relatively flat-lying sediments of the plains (Fig. 2). This explains the abrupt change from the steeply inclined beds of the Foothills structure to the gently folded strata of the plains (Fig. 3). In fact, the fault that underlies Turner Valley and emerges east of the east flank of this structure is the structural boundary between the Foothills

FIG. 3. Looking west across Turner Valley to the mountains. The road in the foreground runs west; the bench crossed in the center foreground is the approximate Edmonton (Cretaceous)-Paskapoo (Eocene) boundary and the strata here dip 30° N.E. but flatten eastward. At the bridge over Sheep River (right center) the Edmonton strata are highly disturbed and at this place the low-angled fault underlying Turner Valley is believed to outcrop. This fault parallels the river to the sharp bend (left center) and has been traced N.W. from the bridge for 40 miles to Bow River (Fig. 1). The eastern and western flanks of Turner Valley north of Sheep River are clearly shown, as are the foothills beyond. (Copyright by W. J. Oliver, Calgary, Alberta.)

and the plains. This fault has been traced for a distance of 40 miles northwestward from Turner Valley to its termination north of Bow River. A few miles south of Bow River, drilling in the Jumpingpound structure (Fig. 1) has shown that here again the fault has a low westward dip. Another fault to the east of the

Turner Valley-Jumpingpound fault, as it may be called, begins south of Bow River and extends northwestward for an unknown distance along the eastern edge of the Foothills. Drilling in the Wildcat Hills area a few miles north of Bow River and west of the line of emergence of this fault has again shown that the fault plane at depth has a low dip to the west. To the south of Turner Valley the low angle fault that passes under the New Black Diamond structure becomes the sole fault under the Highwood area. Thus, in the area between the Highwood and Bow Rivers it has been definitely proved by drilling that the Foothills mass consists of fault plates that overlie one another and have been thrust eastward on low-angle fault surfaces.

Details of Faulting.—Superficially, Turner Valley has the appearance of an anticline on which Belly River (Cretaceous) strata have easterly and westerly dips on the east and west flanks respectively. In reality, however, the structure is that of a drag fold developed above a low-angle thrust and caused by resistance to eastward movement along the fault surface. The strata on the eastern edge, as the block was shoved easterly along the fault surface, have been buckled under; the strata above the fault plane have been broken into a number of blocks by subsidiary faults that join the low-angle fault at depth (Fig. 2). West of Turner Valley, in the New Black Diamond structure, similar structural conditions occur; in fact the whole Foothills belt consists of a series of westward dipping fault blocks, each overriding the fault block to the east of it. Apparently the faults are subsidiary to, and at depth join, low-angle faults that break the Foothills mass into a number of fault plates lying on one another.

REGIONAL STRUCTURAL FEATURES.

Major Thrust Faults.—Overthrust faults of great length and large displacement are a feature of the eastern front of the Rocky Mountains. The Lewis thrust described by Willis [3] and later discussed by Mackenzie [4] has been traced for 50 miles in Montana

[3] Willis, Bailey, "Stratigraphy and Structure, Lewis and Livingston Ranges, Montana," *Bull. Geol. Soc. Amer.*, vol. 13, pp. 305–352, 1902.

[4] Mackenzie, J. D., "The Historical and Structural Geology of the Southernmost Rocky Mountains of Canada," *Trans. Royal Soc. Canada*, vol. 16, ser. 3, sec. 4, 1922.

and 85 miles in Alberta and forms the division between the mountains to the west and the disturbed Foothills belt to the east. The horizontal displacement of the Lewis thrust is measured in miles, and the vertical displacement in thousands of feet. Other large faults have been outlined in the northern Rocky Mountain region of United States. The Heart Mountain overthrust, west of Bighorn Basin, Wyoming, described by Dake [5] and Hewett,[6] has been traced 125 to 150 miles. McCullock Peak, in which Madison (Mississippian) limestone overlies Cretaceous strata, is now 28 miles east of the thrust front but was at one time a part of this great overthrust mass. The horizontal displacement of this fault was therefore at least 28 miles. The Bannock overthrust of southeastern Idaho and Utah has been traced by Mansfield [7] and others for approximately 270 miles and has a horizontal displacement of 12 to 35 miles. Many other large thrust faults are known, and in fact the great overthrust faults are the predominant structural feature of the northern Rocky Mountain region of the United States and southern Canada.

CHARACTER OF FAULTED SURFACE AND AGE OF FAULTS.

According to Willis,[8] the overthrusting was preceded by folding but a sufficient interval elapsed between the folding and the faulting for the development of the "Blackfoot peneplain" on which the edges of some of the formations were exposed. Some of the competent Algonkian strata were thus left unsupported on their eastern edge and further compression caused these to ride forward over the erosion surface. This type of fault emerged at a steep angle and then flattened abruptly to conform to the eroded surface, that is, in a rough way the fault plane was convex upwards. Daly [9] and Mackenzie [10] have both argued

[5] Dake, C. L., "The Heart Mountain Overthrust and Associated Structures in Park County, Wyoming," *Jour. Geol.*, vol. 26, pp. 45–55, 1918.

[6] Hewett, D. F., "The Heart Mountain Overthrust, Wyoming," *Jour. Geol.*, vol. 28, pp. 536–557, 1920.

[7] Mansfield, G. R., *U. S. Geol. Surv.*, Prof. Paper 152, 1927.

[8] Willis, Bailey, *Bull. Geol. Soc. Amer.*, vol. 13, p. 340, 1902.

[9] Daly, R. A., *Geol. Surv. Canada*, Mem. 38, 1912.

[10] Mackenzie, J. D., *Trans. Royal Soc. Canada*, vol. 16, pp. 97–132, 1922.

against a period of peneplanation prior to the Lewis overthrust. Such an erosion cycle would call for a considerable lapse of time and hence the Lewis thrust would have to be assigned to late Eocene if the erosion cycle was completed as stated by Willis. According to Mansfield,[11] however, "later work, mostly unpublished, by geologists of the Federal Survey, in regions east of the mountains not visited by Willis, shows that this fault is either of late Eocene or early Oligocene age."

According to Hewett,[12] the Heart Mountain overthrust moved over a surface "cut across a sharply folded belt of rocks that range from pre-Cambrian granite to beds that appear to represent horizon A of the Bridger formation" (middle Eocene). It is obvious therefore that the faulted mass moved over an erosion surface and the fault is post-Bridger in age. In southeastern Nevada Longwell[13] has recorded the Keystone fault driven forward onto an erosion surface of coarse conglomerate containing pebbles and large boulders derived from the formations in the overthrust mass. "Apparently these fragments," according to the author, "were eroded from the front of the thrust plate, deposited in front of it and overridden as the movement continued." This type of fault, like the Lewis thrust, emerged at a steep angle and then flattened abruptly to conform to the erosion surface. This evidence points to a long period of erosion prior to faulting but, as pointed out by Hewett, it is improbable that all the great overthrusts took place simultaneously, and Mackenzie favored a periodic relief of stress with the faulting in Canada belonging to the end phase of the Laramide revolution. There is no way, however, to date precisely the faulting in Canada except that it is known to be post-Early Eocene. The thrust surface of the low-angle faults under the Foothills in the area between the Bow and Highwood Rivers is an actual break across the formations and not an erosion surface. There is a strong probability, however, that the mountain front may have at one time been much farther east than at present and in Canada the

[11] Mansfield, G. R., *op. cit.*, p. 382.

[12] Hewett, D. F., *op. cit.*, p. 554.

[13] Longwell, C. R., *Bull. Geol. Soc. Amer.*, vol. 37, p. 570, 1926.

Foothills may have been partly if not wholly covered by the fault plate of which the present eastern front of the mountains is the face. There is no doubt that prior to the main thrust faulting in northern United States, the time was sufficient for extensive

FIG. 4. Crowsnest Mountain. (From International Congress Guide Book No. 9, p. 36, 1913, Geol. Surv. of Canada.)

erosion. Hewett, in describing the Heart Mountain overthrust, has shown that McCullock Peak, now 28 miles from the thrust front, is in reality an erosion remnant of a fault plate that at one time extended this far eastward. The large amount of erosion necessary to remove all trace of the overthrust mass in the area intervening between the present thrust front and McCullock Peak is a measure of what might be expected to occur in other areas where the thrust faulting was of the same age. As the Foothills in Canada are nowhere more than 25 miles wide, it is possible that the Paleozoic fault plate of the mountains may at one time have partly or wholly covered them.

The mountains are for the most part sharply defined topographically from the Foothills and the division is clearly apparent because the mountains are composed mainly of massive limestones that are in striking contrast to the sandstones and shales composing the Foothills. The mountain front is mainly the face of a large overthrust overlooking the Foothills, and it appears that the

structural difference between the Foothills and mountains is not in type of structure but in magnitude of overthrusting. There are in Canada some outliers of the mountain thrust plates as, for example, Crowsnest Mountain (Figs. 4, 5) which is 2 to 3 miles

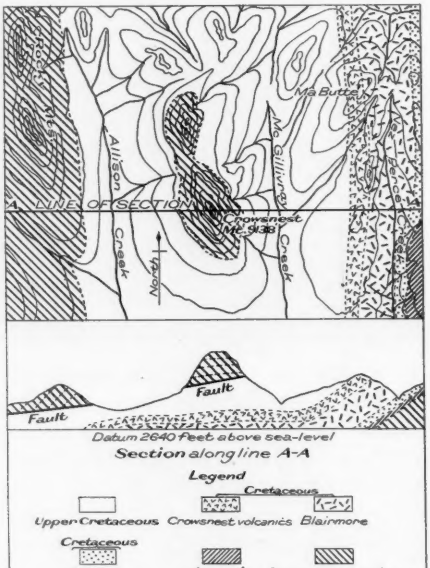

FIG. 5. Map and section of Crowsnest Mountain, Alberta, showing overthrust of Paleozoic on Cretaceous rocks. (From International Congress Guide Book No. 9, p. 36, 1913, Geol. Surv. of Canada.)

east of the present thrust face. Other such outliers occur, and although none is so far removed from the present thrust face as is McCullock Peak from the Heart Mountain overthrust, yet they do indicate extensive erosion and show that the retreat of the thrust plate front from its original position is measured in miles.

Suggestions that a mountain thrust plate may have at one time

covered the Foothills in part or entirely can be seen in the character of the Foothills themselves. The ridges in the eastern Foothills are low and well rounded whereas those in the western Foothills are much higher and sharper. This in itself suggests that the western ridges are less eroded than the eastern ridges, a condition that would result from a gradual recession of the front of an overthrust mass overlying them. It is difficult, however, to estimate the value of this physiographic evidence, since many of the higher ridges to the west consist of slightly coarser materials than those of the east, this being the result of the derivation from the west of the sediments composing the non-marine formations that form most of the ridges. Another suggestion that the Foothills belt may have been partly or wholly covered by an overthrust mass is found in the rarity of surface evidence of low-angle thrusts. If, since the Foothills have been overthrust, a large amount of erosion has taken place, it would be expected that the present fault blocks or fault plates would be eroded sufficiently to expose the underlying low-angle thrusts. The lack of "windows" is regarded, therefore, as a suggestion that the apparent lack of deep erosion may have been due to a protective cover of a higher fault plate that has subsequently been removed, but below which erosion has not proceeded to any appreciable depth. Then too, the major lines of drainage are for the most part superimposed on the present surface. Where any structural influence on drainage is apparent it can be attributed directly to a blocking of old channels by glacial debris. East of the eastern edge of the Foothills there are in a few places huge blocks of quartzite quite unlike any rocks seen in the Foothills but suggestive of rocks known in the mountains to the west. These blocks have been regarded as erratics but their occurrence in three places, each about equally distant from the edge of the Foothills, suggests the possibility of erosion remnants, although there is no proof that such is the case. One of these blocks east of Turner Valley is about 55 feet wide and 160 feet long and at least 25 feet high but is broken into two parts (Fig. 6). A few smaller blocks occur in the immediate neighborhood. These blocks must have been transported long distances from the west. It is difficult

to understand, if ice was the transporting agency, why the blocks would not be broken up and strewn over a wide area. The size of the blocks and their occurrence along a line which in a rough way parallels the foothills belt therefore suggests erosion remnants of a fault plate which at one time covered the entire foothills in this area.

If in the Turner Valley area the mountain thrust plate at

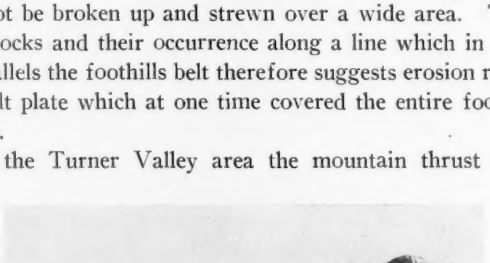

FIG. 6. Large blocks of quartzites east of Turner Valley. Photo by J. G. Spratt.

one time covered all or part of the Foothills, the fault surface under it must have cut across the strata composing the Foothills. This is decidedly the reverse of the Lewis, Heart Mountain, and other large fault blocks, which were thrust onto an erosion surface. The mountain thrust plate in the Highwood-Bow River area would have a counterpart comparable to the Lewis and Heart Mountain thrust if at one time it extended onto the erosion surface of the plains east of the Foothills.

RELATION OF FOOTHILLS TO MOUNTAIN DEFORMATION.

Chamberlin [14] has proposed and applied a method of deducing the thickness of deformation in mountain-building provided that the amounts of crustal shortening and uplift can be measured. He has concluded from his studies that there are two types of

[14] Chamberlin, R. T., *Jour. Geol.*, vol. 18, p. 228–251, 1910; vol. 27, pp. 145–164, 225–251, 1919.

deformation in the Rocky Mountains: (1) deep-seated deformation accompanied by igneous activity, as in Colorado, where a thick crustal shell was involved in the crustal warping; (2) thin shell warping in Alberta accompanied by great overthrusting and no igneous activity. In Canada the Rocky Mountain system is characterized by long parallel ridges changing only in trend, but in Montana, as pointed out by Flint,[15] "this arrangement breaks up and the Rockies gradually come to be represented by irregular mountain groups such as Bridger, Big Snowy and Big and Little Belt mountains, some of which are the result of igneous intrusion. . . . From southern Wyoming to the southern end of the Rockies open folding is the structure dominating the whole group." As noted by Stebinger,[16] the disturbed belt in front of the Lewis thrust is 20 miles wide in the Blackfeet Indian Reserve but toward the south, with the intervention of a mountain range of Paleozoic rocks between the Lewis overthrust and the plains, folding becomes prominent and faulting subordinate in the Cretaceous and Tertiary formations. In the Sun River district south of the Blackfeet Indian Reserve, folding extends up to the base of the mountains. The Foothills disturbed belt is therefore apparently confined to northern Montana and Canada, where it extends from the International Boundary to north of Peace River. In the Mackenzie River valley at the great bend of the Mackenzie west of Fort Simpson, gentle folding extends up to the base of the mountains with little or no faulting, the disturbed belt thus being entirely absent. It may be concluded, therefore, on the basis of the Chamberlin theory of mountain deformation, that the Foothills are a structural belt associated with a particular part of the Rocky Mountains in which it is conceived the deformation was of the thin shell type.

OIL DEVELOPMENTS IN THE FOOTHILLS.

Drilling has been done in many places in the Foothills, but attention is drawn here to developments in the area between Highwood and Bow Rivers. This includes the Turner Valley gas

[15] Flint, R. F., *Jour. Geol.*, vol. 32, p. 411, 1924.

[16] Stebinger, Eugene, *U. S. Geol. Surv.*, Bull. 691–E, 1918.

and oil field, which had a production of almost a million barrels of oil in 1929 and will exceed that amount in 1930. The section (Fig. 2) on which the structure of Turner Valley is shown has been made by projecting certain data on an assumed strike and although it is believed to approximate the type of structure it may not show the exact conditions in any one line of section. Oil is produced from several zones in the Lower Cretaceous and the main naphtha production with gas comes from the Paleozoic limestone. As has already been shown, Turner Valley is in reality a drag fold developed above a low-angle thrust which at depth cuts the Paleozoic limestone. As is shown in Fig. 1, this low-angle thrust emerges at the surface east of Turner Valley and its outcrop has been traced in a northwest direction for 40 miles to Bow River. To the west of its line of emergence the structure seems to be everywhere of the same type but exposing a great variety of geological horizons. Drilling has been done in those places where the apparent anticlinal conditions expose the lowest stratigraphic horizons, *i.e.* in Turner Valley and in the Jumpingpound structure and north of Bow River in the Wildcat Hills, where another fault east of the Turner Valley-Jumpingpound fault becomes the eastern fault of the Foothills. It has been found, however, that whereas the low-angle fault in Turner Valley cuts below the top of the Paleozoic limestone productive of gas and oil, the fault was encountered in two wells drilled in the Jumpingpound structure and one well in the Wildcat Hills structure at higher stratigraphic horizons, and the wells passed through it without reaching the productive limestone horizon. It may be possible, however, to reach the limestone above the fault on the west side of the Jumpingpound structure but a test of this possible condition will require fairly deep drilling and no such attempt has yet been made.

To the south and west of Turner Valley is the Highwood anticlinal area (Fig. 1.) A low-angle fault cuts under this area and hence the structural conditions are believed to be similar to Turner Valley. Erosion over the Highwood area has been deeper than in the Turner Valley area and wells so far drilled have shown that the Paleozoic limestone can be reached by the

drill at a depth of from 2000 to 3000 feet. The Highwood anticline can be traced northwestward for 40 miles to its termination at Jumpingpound Creek. It is not everywhere of the same structural height, however, and from the standpoint of possible oil production three structurally high areas are worthy of attention. These are: (1) the faulted anticlinal area in the vicinity of Highwood River known here as the Highwood anticline; (2) the Fisher Creek structure; and (3) the Two Pine anticline north of Elbow River (see Fig. 1). Low structural areas are Waite Valley between the Highwood and Fisher Creek areas and another unnamed area between Fisher Creek and the Two Pine structure.

Oil Prospects in the Highwood Anticline.—The Highwood anticline is a broad structure. Between the flanking Belly River (Montana) ridges that are considered to be the boundaries in the Turner Valley structure, the Highwood anticline on Highwood River is 6 miles wide. Within it there are several fault blocks forming high structural areas and exposing Lower Cretaceous strata. Four wells have been drilled and in three of these shows of oil and salt water have been encountered in the Paleozoic limestones. This suggests that the oil may be distributed so widely in a number of high structural areas that none of them may have received a sufficient quantity to yield commercial production. Whether this is the case in all these high structural blocks is conjectural but at least it seems to point to rather limited areas of production for this wide anticlinal structure. If the oil is too widely distributed, as suggested, a much narrower anticline, where a better concentration would be possible, would offer more favorable prospects. Such a condition exists in both the Fisher Creek and Two Pine areas.

Oil Prospects in the Fisher Creek and Two Pine Areas.—In the Fisher Creek and Two Pine areas (Fig. 1) the lowest strata exposed (Lower Cretaceous in age) occur mainly in one large area in the central part of the anticline and are flanked on the east and west by higher beds. This condition should favor concentration of the gas and oil present into the central part of the anticline, and that such seems to be the case is attested by the presence of gas seepages on both structures. Such faults as are present

seem to have a high dip on the surface but probably may be less steep at depth where they join low-angle faults that undoubtedly underlie both structures. In the case of the Two Pine anticline the Signal Hill well, being drilled at some considerable distance down the west flank, has reached the top of the Jurassic shales and from a study of the structure in the Fisher Creek area the Paleozoic limestone would be expected at a reasonable depth and above any low-angle fault that might occur under the structure (Fig. 2). A well is now being drilled to test the prospects of this area and both it and the Two Pine anticline are favorably regarded.

OIL FIELDS IN STRUCTURES SIMILAR TO THE ALBERTA FOOTHILLS.

The Foothills of Alberta are so complicated structurally that even with the present yearly production of more than a million barrels of oil from Turner Valley, some doubt might exist that oil could be found elsewhere in them. The results of drilling in the Foothills of the Polish Carpathians of Galicia, where the structure [17] is thought to be similar, are thus instructive and encouraging for future developments in Alberta. Redfield [18] has summarized conditions in Galicia as follows:

> The Polish Carpathians are characterized by a roughly parallel series of extensive overthrust faults, the overthrust mass of each fault overriding that of the fault to the north. In places the overthrusting has been so intense that two, if not more, overthrust masses lie upon one another. Such intense overthrusting has generally caused intense folding with much minor faulting. The resultant anticlines and synclines range from gently symmetrical to highly overturned and recumbent folds, some of which are ruptured along the crest and grade into overthrust faults. In the steep overturned and overthrust folds of the Carpathians with their alternating beds of porous sandstone and impervious shale, petroleum natural gas and mineral wax or ozokerite have been produced in Galicia in a belt about 270 miles long and about 30 miles wide, commencing near Cracow and extending in an arc almost to the eastern boundary of Poland. Over 70 per cent. of the oil produced in Galicia, however, has come from an area comprising 9½ square miles. This area includes the Boryslaw-

[17] Freidl, K., *Pet. Zeit.*, Sept. 11, 1929.

[18] Redfield, A. H., Report No. III, U. S. Federal Oil Conservation Board, pp. 113–114, 1929.

Tustanowice-Mraznica field, which has produced from 1898 to the end of 1927 about 20,517,800 metric tons (approximately 100,000,000 barrels) of petroleum, exclusive of a considerable amount of oil which is burned at the wells for fuel or wasted. The oil-bearing anticlines range from gently to steeply overturned folds, and these may form parts of the overthrust masses at the surface or of the overridden masses lying beneath one or even two or more overthrust faults. The crude oils of Galicia vary in gravity from 53.5° A.P.I. at Bitkow to 25.5° A.P.I. at Harklowa.

This description seems to show that the structure is similar in character to that found in the Foothills of Alberta. It is somewhat difficult to compare the Carpathian and the Alberta Foothills fields in relation to grade of oil. It is a well known fact that under apparently similar structural conditions two fields may yield different grades of oil from strata of the same age, although it is believed that in general the quality of the oil has been affected by the amount of metamorphism to which the sediments containing the oil have been subjected. In general the highest grades of oil are found in the older formations and hence, as would be expected, the Paleozoic limestones of Turner Valley yield a higher grade of oil than that found in Galicia, where the production comes from Tertiary and Cretaceous strata. It is not impossible, however, that crude oil may be found in the Paleozoic of the Alberta Foothills, as was indicated by the shows of oil found in the Highwood wells. The Schodnica, the second largest productive field[19] in Galicia, yields oil from Cretaceous strata, and oil is found in Turner Valley in several Lower Cretaceous horizons. It is evident, therefore, that even under the intense metamorphism which must have resulted from severe compression with attendant thrust faulting it is still possible to obtain a crude oil production, and this fact in conjunction with the crude oil shows found in the Paleozoic limestone in the Highwood wells leads to the hope that the Paleozoic of the Foothills may yield a heavier grade of oil than is the case in Turner Valley, where a very large wastage of gas, for which there is no present market, has created some serious conservation problems.

GEOLOGICAL SURVEY OF CANADA,
OTTAWA, CANADA.

[19] *Petrol. Zeit.*, vol. XXV, No. 18, p. 593, May 1, 1929.

SECONDARY CONCENTRATION OF LAKE SUPERIOR IRON ORES.

C. K. LEITH.

GEOLOGIC conclusions relating to the Lake Superior region have shown many points on which there has been disagreement, but heretofore there has been general acceptance of the idea that the iron ores owe their secondary concentration to oxidizing and leaching solutions moving downward and laterally from the surface. This fundamental concept is now challenged by Professor J. W. Gruner,[1] and it seems appropriate to review his contention, as well as to point out new elements in the problem in the light of fuller knowledge of the ore bodies developed in the course of recent mining and exploration. While the review is critical, there is no intention of questioning the desirability of any attempt to throw new light on this problem.

Professor Gruner offers an interesting hypothesis (though presented more in the form of a conclusion), that the Lake Superior iron ores owe their secondary concentration to hydrothermal solutions emanating in the main from Keweenawan basic intrusives, and in the Vermilion district to earlier acid intrusives. He finds from laboratory experiment that oxidation and leaching of silica are greatly accelerated by moderately high temperatures of 200° to 300° C. He points out supposed shortcomings of the currently accepted hypothesis of surficial weathering. He cites local relations of ores with igneous rocks, the local presence of supposedly hot water minerals in the ore, and local structural details which seem to him to favor the idea of ascending hot solutions rather than descending solutions from the surface.

[1] "Hydrothermal Oxidation and Leaching Experiments; Their Bearing on the Origin of Lake Superior Hematite-Limonite Ores," by John W. Gruner, ECON. GEOL., vol. XXV, pp. 697–719, 837–867, 1930. "The Soudan Formation and a New Suggestion as to the Origin of the Vermilion Iron Ores," by John W. Gruner, ECON. GEOL., vol. XXI, pp. 629–644, 1926.

There is general agreement that large parts of the Lake Superior iron formations were originally ferrous minerals, mainly siderite and greenalite, interbedded with silica and with some layers of original ferric oxide. The exposed parts of the iron formations, amounting to about 225 square miles, where not previously anamorphosed into amphibole magnetite rocks, are now mainly oxidized to jasper, ferruginous slate, and ferruginous chert. The original ferrous portions of the formation are found only in scattered remnants, usually beneath the surface, in places protected by a variety of special conditions from surface oxidation. Over considerable areas in the Marquette and Crystal Falls districts of Michigan the mantle of oxides over the carbonates is thin and discontinuous, perhaps in part due to glacial erosion. No one has heretofore found any difficulty in accepting weathering as the cause of this wholesale oxidation, even though laboratory experiments might show that the process could be accelerated at higher temperatures.

The concentration of the Lake Superior iron ores has included not only oxidation but very extensive leaching of silica. With the old tradition of the insolubility of silica under ordinary weathering conditions, it is not surprising that many geologists have found difficulty in accepting the conclusion that weathering agencies are adequate to accomplish this work, and it is to this phase of the problem that Gruner's arguments are mainly directed. That heat facilitates leaching of silica by pure water has long been known, and this factor has been carefully considered in its relation to the Lake Superior problem. Gruner seems to have overlooked the work of Lenher[2] and his associates who, prior to 1921, presented experimental evidence of the efficacy of hot solutions in leaching silica. In fact the increased solubility of silica at higher temperatures was known long before this. The question, therefore, is not a new one based on new experimental evidence, but remains where it was,—a matter of field evidence. Professor Gruner concludes that field evidence favors the hypothesis of ris-

2 "The Solubility of Silica," by Victor Lenher and H. B. Merrill, *Jour. Amer. Chem. Soc.*, vol. 39, pp. 2630–2638, 1917. "Silicic Acid," by Victor Lenher, *Jour. Amer. Chem. Soc.*, vol. 43, pp. 391–396, 1921.

ing hot waters, but few geologists familiar with the field will find his evidence convincing. There is a tendency to emphasize special and local details at the expense of considerable distortion of perspective. We may analyze some of the principal arguments more in detail.

Gruner asks the question, "If weathering produced deposits in the Lake Superior region, why was such a universal geologic process not more active in the other iron formations?" The answer is that it was, wherever the iron formations were in an original condition comparable to the ore-bearing parts of the Lake Superior iron formations. Highly metamorphic and coarsely crystalline iron formations have resisted the process, not only in the Lake Superior region, but in many other parts of the world. Nor has the leaching of silica by weathering been confined solely to iron formations. There is abundant quantitative evidence that the leaching of silica is highly characteristic of weathering in general, and that enormous quantities have been taken out in the ordinary weathering of acid igneous rocks or in the special weathering of types which have produced laterite and bauxite.[3] Ordinary weathering of granite results in a loss of 30 per cent. of its silica, and even solution of much of the free quartz in cases of thorough weathering. Except under very special and local conditions alumina and ferric oxide have been relatively more resistant to leaching, and where silica can be measured against these elements it is almost without exception found to have been leached. Where, however, the silica is associated with a highly soluble formation like limestone, it remains behind, and this may largely account for the tradition of the insolubility of silica. It happens that the silica of the Lake Superior iron formations is associated only with resistant iron minerals with the result that its loss by leaching can be easily detected. If it had been associated with lime, or magnesian carbonates, or other easily soluble minerals, it doubtless would have been more difficult to prove from local evidence that silica had been extensively leached.

The point is made that notwithstanding the general occurrence of Lake Superior ore bodies at or near the erosion surface, a few

[3] Metamorphic Geology, by C. K. Leith and W. J. Mead.

deep ore bodies have been found which do not connect with the surface. It is to be remembered that there were several pre-Cambrian erosion surfaces in addition to the present one (see later pages). I do not know of a single major ore body which does not connect with one or another of these erosion surfaces. The deepest large ore bodies in the region, those in the Gogebic and Marquette districts, have obviously direct connections. Here and there in the progress of exploration, seemingly detached ore bodies are found below the surface, and at any stage in the exploration isolated cases of this kind could be cited, but I know of no case in which exploration has been really complete where these ore bodies have not been ultimately connected with the surface, usually through ore extensions and occasionally through more or less obvious channels of circulation.

In some of the cases cited by Gruner too much emphasis is placed on direct downward movement, and not enough on horizontal components of movement which are often much longer than the vertical components. Although most of the ore of the Ely trough lies under a capping of jasper, as Gruner states, it does come to the surface at the west end of the trough. The vertical component is about 1400 feet and the horizontal component is 8000 feet. In the Gogebic district, continuous ore bodies have been followed down dikes pitching at low angles to where they are vertically below several other parallel dikes and large masses of unleached iron formation. The vertical component is 3000 feet and the horizontal about 15,000 feet. In the Negaunee basin the soft ores of the footwall pass from the outcropping eastern edge down the gentle pitch of the synclinorium for two or three miles, where what seems likely to be the extension of a continuous ore body is found by drilling through about 3000 feet of unconcentrated iron formation. In these cases the absence of vertical solution channels to the surface and the presence of heavy unleached capping have little bearing on the question whether surface waters did the work. If deep ore bodies unconnected with surface channels should be found to exist, they would present the same problem of escape for silica-laden hot waters from below as for ingress of waters from above.

The objection is made that the oxidizing and leaching power of surficial water would be lost long before reaching such depths in the iron formation even if the flow were active, but this objection seems to be countered by the fact that the result of leaching and oxidation at the surface is to create a product that has no effect whatever on incoming waters. In other words, each newly arriving unit of water may travel an indefinitely long distance through the oxide products without chemical change before it begins its work on the unleached and unoxidized formation below. Its effectiveness is not confined to the zone above the water table, but may extend as far below as circulation is active.

The fact that all the ore bodies do not widen above, that some are wider below with steep or overhanging walls, and are often highly tortuous, is hardly evidence of upward-moving solutions in face of the overwhelming preponderance of ores on or near the erosion surface. Irregularity is inherent in such conditions. Waters use all the available cross sections of whatever channels exist.

To explain the fact that many ore bodies are on the upper side of pitching troughs of impervious rocks, either structural synclines, or some combination of sedimentary and igneous intrusives furnishing the same structural conditions, Gruner argues that there are many more synclines without ore than with ore; that there are many ore bodies which are not in definite troughs; that any synclinorium cut by erosion will have more synclinal than anticlinal surface, and that therefore there is mathematical probability of more ore on synclinal than on anticlinal surfaces; finally that upward-rising hot solutions could concentrate ores in synclines under certain special conditions. It has long been recognized that while the synclinal occurrence of the ores is highly characteristic, they also follow bedding planes, joint and fault planes, and even the axial lines of pitching anticlines where these have been opened up by the deformation, but this does not minimize the validity of the inferences drawn from undoubted synclinal occurrences. How then are such occurrences to be explained by rising hot solutions? Are rising solutions more likely to choose synclines than anticlines just because there are more synclinal areas?

It is suggested and illustrated by diagram that solutions rising along the main limb of a synclinorium would follow up its corrugated main limb bottom and would be prevented from entering the minor anticlines of the drag folds by the trapped gas pressures, thus accounting for some of the trough or drag fold ore bodies of the Menominee, Crystal Falls and Iron River districts. Disregarding great theoretical difficulties in this novel concept of the movement of rising solutions, I do not know of a single ore body in these districts which on analysis shows any approach to the postulated conditions. Closed domes suitable for trapping are very rare; most of the folds are pitching; ore sometimes makes in anticlines, as in the Judson and other mines in the Crystal Falls district and the Aragon in the Menominee district, but such occurrences can be definitely related to structural openings in axial zones which are traversed by surface waters. No explanation is offered of the way hot waters could get above the impervious layers in many cases of gently pitching open basins like the Negaunee synclinorium.

As for the ore in pitching troughs formed by the intersection of basic dikes and quartzite in the Gogebic range, the hot solutions are supposed to be effective "clearly above the dikes, where the heat was most intense." Why above rather than below? Also which side was above and which below at the time the dikes were intruded? The evidence is clear that they were then nearly vertical, that they have been subsequently tilted with the folding, and that only after or during the tilting has the ore concentration occurred. If rising hot solutions did the work after tilting, why was ore not concentrated on the lower side of dikes? Why do the ore bodies so generally blanket the footwall quartzite, or follow fracture zones from the surface, whether dikes are present or not? Ore in places breaks downward through faulted dikes, not upward, indicating concentration from above later than intrusion. The fact that some of the dikes pitch westward while most of them pitch to the east is regarded by Gruner as a condition which should have greatly complicated progress for descending waters. The canoe-shaped basins so formed are favorite places for concentration, and it is difficult to see what complication Gruner has

in mind in view of the many avenues of escape through cross and parallel faults. Where dikes are parallel and closely spaced the ore rests on the uppermost one. If upward-moving solutions from dikes leached the silica, presumably the same argument should apply to the great basic sill of the eastern Gogebic, but in this case the ore is below, not above, though still on the upper sides of associated dikes. Ore is not found under the Duluth gabbro where it lies on the Mesabi iron formation. It is found in highly varied relations to basic dikes and laccolites in the Marquette district. In the Vermilion district, the source of the hot solutions is attributed to acid porphyries and not to basic intrusives. The porphyries stand in intricate structural relations with the ores, as well as cutting both iron formation and other rocks entirely away from the ores. Heavy basic dikes crossing the Magpie siderite formation in the Michipicoten district have only the characteristic contact-metamorphic effects, the change of the iron carbonate to magnetite with *increase* of silica,—not leaching of silica or formation of hematite. Similar dikes in the Helen siderite formation of the same district have the same effect, but a few hundred yards away the Helen hematite ore body was bottomed in siderite.

The fact is that dikes and sills and laccolites and bosses may be above or below ore, or on one side or the other of ore, or within ore. Some are in the iron formation and not near ore. Some are basic and some are acid. Their main rôle, aside from local contact-metamorphic effects, seems to be the damming of channels of downward and lateral flow. It is a remarkable coincidence that ore bodies have much the same space relations to containing rocks whether such rocks are igneous or sedimentary, whether they are basalt, granite, dolomite, talc schist, quartzite, graywacke or slate.

Much the greater part of Lake Superior deposits are not associated with igneous rocks at all. No igneous intrusions or extrusions are known in the Menominee district, and here several important shoots of ore have bottomed below in unleached iron formation where there is no known channel for the entrance of solutions from below. In the Mesabi district the only large mass

of intrusive, the Duluth gabbro, covers the eastern fifty miles of the district, with contact-metamorphic but no leaching effects. A few small dikes, both basic and acid, are known east of Aurora, none of which show any relations to ore bodies even faintly suggestive of leaching effects. In the seventy-five miles of iron formation west of Aurora, containing nearly all of the Mesabi ore, no dikes are known. Recognizing the essential absence of dikes in the iron formation itself, Gruner refers to a few dikes in the Giants Range complex unconformably beneath the iron-bearing series, with the suggestion that they might be later than the iron formation and that "they are testimony that large basic intrusives are concealed under the Mesabi range." Pebbles of these dikes exist in the basal conglomerate of the iron-bearing series, as northwest of Biwabik, and there is not one shred of evidence that any of them are later than the iron formation. Nor is there any evidence of orogenic disturbance after the deposition of iron-bearing series which is suggestive of large-scale intrusive at this time. The complete absence of ore in the iron formation under the impervious Virginia slate, where hot solutions might be supposed to concentrate, is vaguely ascribed to the flow of hot solutions and gases in a narrow zone between the Giants Range granite and the thinnest fractured portions of the Virginia slate,—a concept difficult to understand or to reconcile with the structural conditions. In recognition of the weakness of the positive evidence for hot solutions in the Mesabi district, Gruner puts his emphasis on supposed shortcomings in the weathering hypothesis to explain details of the ore occurrence. None of the details cited are new, and none have heretofore been regarded as not in accord with the hypothesis of leaching from above.

It remains to ask what evidence there is that either acid or basic intrusives in the Lake Superior district or elsewhere actually have oxidizing and leaching effects on any rocks with which they contact, whatever inferences might be drawn from experiment. In connection with our studies of metamorphism we have platted up all available analyses showing the contact and hydrothermal effects of both basic and acid intrusives.[4] In the very great majority of

[4] Metamorphic Geology, *cit.*, also more recent analyses.

cases silica is increased relative to aluminum and iron, and ferrous iron is increased at the expense of ferric iron. The Magpie case has already been cited. Many marked cases of intense silicification by hot solutions are known in western mining districts. There are only a few explainable exceptions showing minor decreases of silica, but not one showing abstraction of silica on the scale required by the present problem. The fillings of amygdules and wall rock alterations in Keweenawan extrusions show that the thermal waters were heavily laden with minerals. In general, the evidence is conclusive that thermal waters emanating from intrusives and extrusives, both in the Lake Superior region and elsewhere, are pretty fully charged with mineral content, and that their action is that of replacement and deposition and not of leaching.

The Lake Superior ores represent the leaching of immense quantities of silica which must have required great volumes of water. Scale alone puts a very heavy burden of proof on the contention that the scattering small dikes in several of the ranges could serve as evidence of the existence of the necessary volumes of water.

The presence of talc, serpentine, chlorite, hematite, and martite in or near some of the Lake Superior ore bodies is construed by Gruner as evidence of hot solutions. Most of these minerals we think can be better connected with weathering conditions or dynamic metamorphism. Talc schist, for instance, is formed by the shearing of the footwall dolomite of the Menominee district, which is a characteristic result of dynamic metamorphism of such rocks independent of thermal solutions. Detailed studies of martite have shown it to be formed both by slow oxidation at ordinary temperatures and under thermal conditions.[5] But this is a long story. The iron formations of the Lake Superior region have had complex metamorphic histories and have suffered both anamorphic and katamorphic alterations. Igneous intrusives have had their characteristic thermal and contact effects. The essential fact is that the ores as a whole are remarkably free from minerals

[5] Lillian H. Twenhofel, "Changes in the Oxidation of Iron in Magnetite," ECON. GEOL., vol. 22, No. 2, pp. 180–188, 1927.

of a possible hot water origin, and where such minerals are locally present they can be satisfactorily explained as either residual from some earlier phase of metamorphism or as introduced in subsequent phases.[6]

Additional details might be cited to disprove the hypothesis of secondary concentration of the iron ores by ascending thermal solutions, but perhaps enough have been given to indicate insuperable difficulties in the way of its acceptance.

RE-STATEMENT OF THE PROCESS OF CONCENTRATION BY WATERS FROM THE SURFACE.

The accepted hypothesis of concentration of the iron ores by waters from the surface may need expansion and qualification to cover some features of the ore deposits disclosed in developments of recent years. A brief review of the hypothesis will furnish a background for an understanding of these newer elements of the problem. Mining began at or near the present erosion surface, and for a long time little ore was known deeper than a thousand feet. In this distance many ore bodies were bottomed. It was natural, therefore, that early ideas of the ore concentration should relate to the present erosion surface. Even yet there is a good deal of confused thinking on this subject. When development disclosed ore bodies extending to greater depths, it became clear that they could hardly be explained by oxidation under present conditions where the water table is seldom more than 100 feet below the surface, and more attention was paid to evidence fixing the time of concentration and the conditions existing at that time. Several periods of possible concentration are known in the different districts.

1. The iron formation of the Keewatin was exposed to weathering (*a*) in the period preceding the deposition of the Knife Lake slates, (*b*) after the Algoman revolution and preceding the deposition of the Mesabi series and its equivalents, (*c*) in the period of erosion of the Mesabi series and prior to the Keweenawan deposi-

[6] The metamorphic aspects of the problem of secondary concentration of the iron ores will be discussed in a separate paper, now in preparation in the Department of Geology at the University of Wisconsin.

tion, (*d*) in the period following the Keweenawan and prior to the Cambrian. The only commercial ore bodies in the Keewatin are in the Vermilion district, where the record ends with the post-Algoman erosion and where evidences of later erosion cycles are not recorded. The metamorphic history here is complex, but the evidence seems to indicate concentration both preceding and following the Knife Lake slate deposition. Whichever it was, the depth of concentration yet known below the present surface is sufficiently shallow to be accounted for by concentration from either of these old surfaces.

2. At the close of the Negaunee period (Middle Huronian) in the Marquette district and in equivalent horizons of the Crystal Falls and Menominee districts, the iron formation was exposed and surficially concentrated over considerable areas as shown by the nature of the overlying conglomerate which carries boulders both of ore and oxidized formation. The hard ore horizon of the Marquette district was initially concentrated at this time, though it has since undergone metamorphic changes and perhaps additional concentration. This old erosion surface usually dips steeply with reference to the present surface and has been followed to a maximum depth of nearly 3000 feet at the Republic mine. There seems to be no theoretical reason why ore bodies on this old surface should not go indefinitely deeper. In the Crystal Falls and Menominee districts the post-Negaunee surface only locally exposed the iron formation, more or less slate being left as a capping, and in these districts no ore bodies can be definitely ascribed to this old surface.

Newer ideas of correlation are trending toward the belief that both the Gogebic and the Mesabi formations are the same age as the Negaunee formation of the Marquette district, but as yet an unconformity between the iron formation and the overlying slates has not been proved in these districts. There is some indication of it at the east end of the Gogebic range, and also in the Pabst fragmental horizon through the central part of the range where the heavy ore bodies exist. In the Mesabi district no adequate evidence has yet been found.

3. In the Gogebic range the erosion preceding the Keweenawan

deposition beveled the iron formation in the Sunday Lake area and eastward, and the boulders in the basal conglomerate of the Keweenawan show that there was some concentration at this time. This probably was a factor in the concentration of the Brotherton-Sunday Lake-Castile ore bodies, but not of the ore bodies in the main producing part of the range to the westward. There the pre-Keweenawan erosion did not expose the iron formation, which remained blanketed with a thick mass of slate. In Minnesota, any Keweenawan surface beds which may have covered the Cuyuna, Vermilion and Mesabi districts have been stripped away, leaving no evidence for or against surface concentration during the pre-Keweenawan erosion interval.

4. By far the larger part of Lake Superior iron ores, including practically all the soft ores, was concentrated in the post-Keweenawan period of erosion preceding the deposition of the Cambrian. There is no positive evidence that the parts of the iron formations carrying most of the soft ores were ever before exposed to erosion. Basal conglomerates of the Cambrian carry abundant boulders of fully concentrated ore. The erosion surface on which it rests records one of the most striking cases of long continued and deep erosion known in geological history. During this time all the great folds of the pre-Cambrian were truncated. Restoration of these folds shows mountainous conditions, where surface waters must have had a head comparable with that existing today in mountainous regions, where oxidizing solutions are known to penetrate to far greater depths than they do today in the Lake Superior country. Furthermore, this period is known, from the character of the Keweenawan sediments, to have been one of a semi-arid climate under which the water table must have been far below the surface.

Each of the earlier erosion surfaces described in the above paragraphs was beveled by the later ones. In each case oxidation and leaching of silica created porous zones which were utilized by waters from later surfaces. Such predisposition to concentration was undoubtedly an important influence in the efficacy of the great concentration of post-Keweenawan time.

These reconstructed conditions (which were substantially out-

lined over twenty years ago [7]) seem to be adequate to explain concentration by surficial waters to any depths yet known. However, recent exploration has carried one of the Gogebic deposits down to 3000 feet from the pre-Cambrian erosion surface, with the end not yet in sight. This ore may be related to a post-Negaunee erosion surface described under (2), but the evidence of this unconformity is not yet conclusive. If the unconformity does not exist, then the ore must be related to the post-Keweenawan erosion surface. This calls for review of the conditions existing in the post-Keweenawan erosion conditions to explain how oxidizing and leaching waters from the surface could penetrate to such a distance. This is apparently beyond the depth of oxidation known today in any of the semi-arid mountainous regions of the west where the depth of oxidation is presumably a maximum, However, existing information in mountainous regions is mainly confined to a few mining districts, and the ultimate possibilities have perhaps not yet been disclosed. If a depth of 3000 feet proves to be beyond the reach of penetration of the surface waters in a mountainous semi-arid period, modification of our hypothesis may be necessary. Concentration may have begun early in the period of Keweenawan tilting and continued during the Keweenawan folding with the downward migration of the erosion plane, but under the influence of temperatures higher than normal, due to the slow cooling of the thick blanket of Keweenawan lavas and its associated intrusives. Ore bodies so formed, before the tilting was complete, would be rotated by the further tilting, thus reaching a greater vertical depth. Geological and physical evidences are multiplying that igneous rocks of such mass cool very slowly, raising the question whether an inheritance of heat from this source may have accelerated the leaching of silica from the ores by ordinary surface waters through a very long period. This might help to explain the fact that so much of the concentration took place before Cambrian times and so little since. The process is the same in kind before and since, but the striking difference in degree has heretofore been taken as just another evidence of the

[7] "The Geology of the Lake Superior Region," by C. R. Van Hise and C. K. Leith, U. S. Geol. Survey, Monograph 52, 1911.

immense length of time represented by the erosion interval preceding the Cambrian.

Although higher temperature will accelerate the process of concentration, it still fails to account for the hydraulics of such deep flow. Waters are ordinarily ponded and stagnant at such depths. For the exceptionally deep ore bodies the possibility has been considered that there may be unusually deep and direct channels both for inlet and outlet of waters that might carry active artesian circulation far below the normal water table, as in the case of a stream carried in an inverted pipe elbow. Several years ago Mr. James Thompson, one of the successful explorers of the Gogebic range and the discoverer of the deep Newport ore body, worked on the assumption that the ore body might continue eastward down the pitch to a depth of two miles or more, until intersected by a cross fault known in the vicinity of Bessemer which would serve as the outlet. It is difficult to prove or disprove such an hypothesis on theoretical grounds, and the deep ore bodies in question have not been developed far enough to show whether or not such outlets to the surface exist. If an unconformity exists between the iron formation and overlying slates, which is possible, as already indicated, this would afford a porous zone of easy flow. It should be noted, also, that so far as concentration occurred before the Keweenawan tilting was complete, the ore was nearer the surface than today, which would make it easier to postulate artesian circulation with cross faults as outlets.

In the Marquette district soft ore has been found by drilling to a depth of 3000 feet below the surface. This ore lies along the extension of the Negaunee mine and contiguous ore bodies that connect directly with the surface, and it seems likely that direct surface connection with the ore in the drill hole will eventually be demonstrated. The iron formation was exposed to weathering before the deposition of the Goodrich quartzite which is the bottom of the next overlying Huronian series. It was also exposed in post-Keweenawan time, and there are various lines of evidence that this was the time of the formation of the soft ores of this district. There is no evidence to indicate whether or not the district was covered by surface flows of the Keweenawan, but intru-

sives of supposed Keweenawan age are abundant. As in the case of the deep ore of the Gogebic range, it is not certain that this ore is beneath the range of active artesian circulation of cold waters from the surface either in pre-Goodrich time or during the long period of peneplanation of mountains which preceded the Cambrian. But again it is possible that the waters from the surface were warmed and that the process was well started before the Keweenawan folding was complete, when the deep concentration now known was much nearer the surface.

In conclusion, the general hypothesis of concentration of the iron ores by downward moving waters from the surface, as presented in Monograph 52, still seems to be adequate to cover the great body of facts yet known, and it is too early to say how far additional qualifications are necessary to explain the few exceptionally deep concentrations which have been found. The problem has a direct practical bearing on estimates of the future Lake Superior mines, and has been receiving close attention for years from geologists concerned in the detailed study of these mines.

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"CAVE PEARLS," OÖLITES, AND ISOLATED INCLUSIONS IN VEINS.

S. C. DAVIDSON AND H. E. McKINSTRY.

DR. FRANK L. HESS has recently published an excellent description of the small rounded balls of calcite which were found in process of formation in pools on the floor of the Carlsbad Caverns in New Mexico by Dr. Willis T. Lee, and by him given the "somewhat fanciful name 'cave pearls.'" [1] Though Hess does not call attention to the fact, it is interesting to note that a very similar occurrence has been described by Dr. W. H. Emmons in the Hidden Fortune Mine at Lead, S. D.[2] The two authors differ on one point regarding the mode of formation of the "pearls"—not in itself a point of vital importance, yet, inasmuch as both investigators draw by analogy certain conclusions regarding broader geological processes, a point which forms an essential step in the chain of reasoning, and has a bearing on the interpretation of inclusions in veins.

Hess, in pointing out the analogy of the "cave pearls" to oölites, says:

> These molecules [of calcium carbonate], attaching themselves to other molecules in the little eddies of a tiny pool, form a spherical body. *They must have been kept in sufficient motion to maintain this form as they increased in size.* The movement of the water caused by the splash of falling drops is probably sufficient. In much the same way oölitic sands have formed on the bottom of the Great Salt Lake. . . . As the lake waters move over the bottom, calcium carbonate is added to the oölites already formed or new ones are started. The size of the oölites is probably related to the *amount of their movement* after they have been formed." (The italics are ours.)

Emmons, on the contrary, makes quite clear his belief that

[1] *Proc. U. S. Nat. Museum*, Vol. 76, Art. 16, pp. 1–5.

[2] "The State and Density of Solutions Depositing Metalliferous Veins," *Trans. A. I. M. E.*, Vol. 76, pp. 308–320.

the fragments were not rolled during deposition, but that the carbonate was added in successive layers around the nucleus both on its lower and upper sides, the fragments being gradually lifted up by the force of crystal growth. He says: "The water is not agitated, the fragments are flat, and they have not rolled over." [3] Furthermore, he describes one fragment, the nucleus of which consists of a steel bolthead coated with a layer of calcite on all sides including the bottom.

The question is: in the formation of structures of this type is it necessary that the fragments shall be rolled during growth? If the answer is "yes," Emmons' conclusions regarding isolated inclusions are scarcely valid. If the answer is "no," the inferences are:

1. Oölites may be formed in still water, the particles being lifted and separated by force of crystal growth, and oölitic textures do not necessarily mean that the grains have been rolled by wave or current action.

2. Fragments lying in open spaces may become surrounded by concentric layers of vein matter, lifted, separated from each other, and eventually become "floating inclusions" surrounded by concentric bands as Emmons has suggested, without the necessity of other forces having interposed to move the fragments and roll them about.

Toward answering this question we offer observations on four new occurrences of "cave pearls" found in Mexican mines.

San Dimas, Durango.—Two of these were discovered during the course of geologic mapping of the old levels in the Arana and Bolaños mines. The argentite-gold veins which cut the Tertiary eruptive rocks of this region (mainly andesite) consist primarily of quartz, associated with which is a considerable amount of carbonate, usually in the form of very fine-grained rhodocrosite.

Both occurrences of "cave pearls" were in drifts which were opened up over 25 years ago and long since abandoned. During the past two or three decades waters charged principally with calcium carbonate have been percolating into the drift along portions of the channel-ways provided by post-ore faults

[3] *Op. cit.*, p. 316.

paralleling the veins, usually along or near the hanging wall. The floors of these old drifts are (in places) coated with a deposit of lime carbonate in the form of miniature terraced deposits several centimeters in thickness.

The "cave pearls" formed by these lime-bearing waters occur usually in shallow nests or pools containing from one or two individuals to, in one instance, several hundred. There are two distinct types of pearls to be seen in both these occurrences and apparently the difference in type is due to a slightly differing mode of formation.

Type 1: Smooth-coated Pearls Covered with Very Finely Crystalline Calcite (*Fig. 1*).—The "pearls" of this type are pure

FIG. 1.

FIG. 2.

white in color, varying in size from 2 mm. up to about 3 cm. in diameter, and although usually round, most of the individuals are of irregular outline. Upon being broken open they are commonly found to contain an angular fragment of andesite or rhyolite around which uniform layers of calcite have grown, thus preserving in a general way the original shape of the nucleus. These smooth-coated "pearls" develop most abundantly where the lime-bearing waters drip from the back of the drift into little pools, resulting in an agitation of the water

but not necessarily of the pearls themselves. The pool previously mentioned as containing hundreds of individuals is about 30 cm. in diameter and about 1–2 cm. in depth. The "pearls" in this pool range from about 1 mm. up to 1 cm. in diameter, and as the water drips rapidly from the back of the drift into it the smaller "pearls" are in a constant state of agitation, in contrast to which the larger individuals of exactly similar type in this same pool are not affected by any visible agitation. In many other pools large smooth-coated "pearls" are not at all disturbed by the dropping of the water from the roof and apparently agitation of the "pearls" themselves is not essential to their formation.

Type 2: Rough-coated Pearls Studded with Crystalline Calcite (*Fig. 2*).—The rough-coated type of "pearl" occurs under somewhat similar conditions to the first type, but usually tends to be perfectly round with a peculiar burr-like appearance. This is due to each concentric layer of carbonate being made up of coarsely (when compared to Type 1) crystalline matter around the nucleus so that the surface of the "pearl" is of rough appearance, being studded with crystals of the order of 1–2 mm. diameter.

The "pearls" of this type are found as groups of individuals in very small depressions in the carbonate-coated floor of the drifts where the lime-bearing waters appear to be circulating more slowly than in the case of the smooth-coated variety.

It would thus appear that the type of pearl found depends on the rapidity with which the lime-bearing water circulates, the smooth-coated variety forming where the solutions circulate rapidly, and the rough-coated variety forming under conditions approaching stagnation.

San Francisco de Yoquivo, Chihuahua.—This is a gold-silver mine in a quartz-calcite vein that cuts andesite. The upper portion of the vein is thoroughly oxidized and leached. On the lowest accessible level, which was opened about 1908 and has been abandoned since about 1920, water is dripping from the roof and calcium carbonate is being deposited on the floor.

The "cave pearls" are in nests very similar to those at

San Dimas, and lie one upon another in the bottom of the basin, quite loose and detached from each other as well as from the bottom of the pool. They are not perfectly round, but ellipsoidal or almond-shaped. In some cases they have concavities or smooth dents where one "pearl" touches another.

Minitas, Durango.—This mine is on the trail between the ranch of Las Cebollas and the mining village of Tayoltita. It was an old silver mine opened by an adit on a vein of quartz-calcite gangue. There was no noticeable difference as regards the pools or the "pearls" from those of the Yoquivo mine. Some of these "pearls" showed similar concavities at the points where they touched each other.

MODE OF FORMATION.

By way of experiment one of the present writers (Davidson) "planted a seed" by placing an angular fragment of andesite about 1 × 2 × 3 cm. in one of the pools of nearly stagnant solution. In the year and a half during which this experiment has been in progress, the fragment has been coated all around with a layer of crystalline carbonate 1–2 mm. thick, and the growth of these crystals has lifted the fragment against the force of gravity from its original position of rest a distance equal to the thickness of the carbonate layer. The layer of carbonate on the under side of the fragment, it is true, is not quite as thick as that on the sides and top, but, nevertheless, it has been raised an appreciable distance and is still unattached at the base.

This evidence that rolling is not necessary is confirmed by observation at all the localities. At Minitas and Yoquivo the present flow of water along the drift is insignificant and the form of stalagmitic deposition is such as to suggest that it has always been so. The pools are still, the drops fall only at the rate of one every few minutes, and the water leaves the pools only by evaporation or by almost imperceptible overflow. At San Dimas some of the pools are stagnant and in others only the smaller fragments are agitated. Furthermore,

the slightly rounded truncations at the contact of one "pearl" with another show that the "pearls" have not been rolled over, at least not during the recent stages of their growth.

CONCLUSIONS.

Our observation of "cave pearls" in all stages of formation convinces us that rolling of the particles is not necessary. The inference to be drawn is that, so far as analogy applies, the size of oölites is not necessarily related to the amount of rolling that they have undergone and that, as Emmons has suggested, ring and cockade textures in veins may be formed by deposition around nuclei of wall-rock which have been separated from each other by force of the growing crystals [4] of the precipitate.

ROTCH BUILDING,
CAMBRIDGE, MASS.

[4] We hope that the present use of this much-discussed phrase will not be misinterpreted. It is generally recognized that, regardless of whether or not the force of crystal growth is sufficient to push apart vein walls, it is fully adequate to detach fragments from the walls or to lift them against their own weight.

A LEAD–ZINC DEPOSIT AT GENEVA LAKE, ONTARIO.

RALPH TUCK.

INTRODUCTION.

THE deposit here described is located in the northern part of Hess Township, Sudbury Mining District, Ontario, Canada, about ten miles northwest of the northwest rim of Sudbury Basin and about thirty-five miles northwest of the city of Sudbury.

Previous Work.—The geological literature on the district is meager. T. T. Quirke [1] has given a short report on the general geology of the Geneva Lake District.

Since this paper was written, a report on the Cartier-Stralak Area, by F. F. Osborne,[2] has appeared in which Quirke's previous work has been revised and the formation in which the Geneva Lake deposit occurs is called pre-Huronian. If this is correct the formation does not appear to have been subjected to any great dynamic metamorphism as is common with the pre-Huronian sediments.

F. F. Osborne [3] has described a diabase contact-metamorphic deposit in the adjoining township of Hart, and similar formations occur in both townships.

Topography.—The topography is typical of the pre-Cambrian of Northern Canada, the maximum relief being around five hundred feet. The most conspicuous features are a number of long ridges that trend northeasterly. Here and there, irregularly rounded hills and small lakes and muskegs occur between the ridges. The largest lake in the immediate area is Geneva Lake, with a maximum length of three miles.

There are no major streams in the area, since it lies close to the

[1] T. T. Quirke, "Geneva Map Area, Sudbury District," *Can. Dept of Mines*, Summary Rept. 1920, Part D, pp. 7–18.

[2] F. F. Osborne, Ontario Dept. of Mines, Ann. Rept. 1929, vol. 38, part 7.

[3] F. F. Osborne, "A Diabase Contact-Metamorphic Mineral Deposit in Ontario," ECON. GEOL., vol. 24, pp. 722–32, 1929.

divide between the Spanish River on the west and the Onaping River on the east.

History.—The discovery of ore deposits in the Lake Geneva District is of somewhat recent date; the greater part of the area is covered by claims, but as yet the most favorable showing is that of the Lake Geneva Mining Co., Ltd.

The surface showing was located in October, 1924, and was indicated by much ferruginous soil which led the prospectors to strip off the several feet of overburden and about four feet of oxidized sulphides, thus uncovering a five-foot vein of sphalerite and galena. Trenching and stripping has exposed the vein for a distance of about two hundred feet with widths varying from two to six feet. To the northwest, the vein pinches and the sulphides show only as a few small stringers; to the southeast it dips out of sight under a muskeg, so that an initial drilling program of two thousand feet was started. By this means the ore has been proved to a depth of 350 feet, a shaft has been sunk and considerable drifting and cross-cutting have been accomplished.

GENERAL GEOLOGY.

The rocks of the Geneva Lake District are all of pre-Cambrian age with the exception of the unconsolidated Pleistocene deposits. They have been divided into two groups; the pre-Huronian and the Huronian. The former are mostly so highly metamorphosed that their original character can not be ascertained with certainty, but they are of no importance in connection with the mineralization.

The less metamorphosed Huronian rocks can be identified with reasonable accuracy, although the intrusives have suffered considerable change, principally by hydrothermal alteration.

The geologic succession is given in Table I, which is for the most part taken from Quirke,[4] with a few changes made by the writer, particularly in regard to the age of the later intrusions. Of the above formations only the Serpent formation and the Keweenawan intrusives are of interest in connection with the ore and they are referred to in more detail below.

[4] T. T. Quirke, *op. cit.*

TABLE I.

GEOLOGIC COLUMN.

Pleistocene—glacial deposits
unconformity
Keweenawan
Olivine diabase—postmineralization
Basic intrusions—norite and pre-mineral diabases
Alaskitic, syenitic, and granitic intrusions
intrusive contact
Cobalt Series
Lorrain quartzite
Gowganda—quartzite, graywacke, and conglomerate
unconformity
Bruce Series
Serpent—quartzite and graywacke
Espanola—thin bedded limestone
Mississagi—conglomerate, arkose, and quartzite
unconformity
Algoman?—granite
intrusive contact
Keewatin—volcanics, schists and gneisses

Serpent Formation.—The Serpent formation is a sedimentary series of varying composition and is the one that contains the ore. Although no commercial bodies of ore have been uncovered in any of the other formations, there appears to be no reason why some of them should not contain ore, since they resemble the Serpent formation in composition and structure.

On the Geneva Lake property, the Serpent formation consists of alternating layers of quartzite, graywacke, and conglomerate, ranging in thickness from a few inches to a hundred feet. The graywacke beds are sheared, whereas the quartzite layers are dense, compact, and have been fractured to only a slight degree. The quartzite and graywacke may exhibit a fine and well developed cross-bedding, with well preserved ripple and rill marks. The conglomerate occurs infrequently as non-persistent lenses, and in the vicinity of the mine they are insignificant.

Megascopically the graywacke is fine-grained, dark green to black in color, and exhibits lustrous crystals of hornblende. The

quartzites are fine to medium in texture, with some arkosic portions. In color they range from white to gray or green, depending on the relative abundance of ferromagnesium minerals.

The Serpent formation as a whole has been formed by rapid deposition of sediments in a shallow sea. This is indicated by the alternating layers, quick vertical change in composition, conglomerate lenses, cross-bedding, and rill and ripple marks.

Microscopically, the quartzites are composed chiefly of well sorted, clear, rounded to sub-angular grains of quartz. There is commonly a small amount of feldspar present and some are decidedly feldspathic. The feldspar is mostly microcline, orthoclase, and albite, and these show varying amounts of alteration, with the development of secondary mica. As minor constituents there are: epidote, biotite, muscovite, chlorite and pyrite.

The graywackes show an abundance of secondary minerals, prominent among them being long, slender crystals of hornblende formed by recrystallization. Some of the hornblende is decidedly sodic in composition and it may show varying degrees of alteration to biotite and chlorite. These last two minerals are always present and in some cases form the major portions of the rock. Epidote is a common constituent and is present in small irregular masses that are evenly disseminated throughout the graywacke.

Orthoclase, microcline and plagioclase are abundant; the plagioclase is least common and ranges in composition from albite to andesine. They are all detrital and their source is probably the underlying pre-Huronian granite, which contains similar feldspar. Rounded and sub-angular grains of quartz are common. Some disseminated ilmenite is present and shows alteration rims of titanite. All gradations exist, between the quartzite and graywacke, the quartz and hornblende being the variable constituents.

Within the Serpent formation, probably near its base and outcropping near the vein, is a breccia with extraordinarily large, tightly-fitting rock fragments, that can be traced laterally for over a mile. It consists of large angular blocks of graywacke, conglomerate, granite, diabase, gabbro, quartzite and limestone, which vary in size from a few feet to fifty or sixty feet, hence on account

of their size it is often difficult to recognize the brecciated character of the mass.

Microscopically the interblock material consists of thin layers of a fine-grained, complex aggregate of quartz, highly altered feldspar, disseminated biotite, muscovite and epidote. Secondary hornblende in long needle-like crystals, small amounts of ilmenite, calcite, leucoxene, pyrite and chlorite also occur. Inclosed in the above matrix are small nodules of quartzite and graywacke. This interblock material may be either a tuff or a fine-grained intrusive but it is believed that the former is more probable.

On account of the magnitude of the blocks, their tight-fitting nature, the heterogenous types represented, and the small amount of interblock material, the origin of this rock is puzzling. An aqueous origin is eliminated due to the magnitude of the blocks; the field relations do not substantiate it as being a tillite; nor can it represent a fault zone, because it is five hundred feet wide in places and shearing or fracturing are not evident.

The most tenable hypothesis is that it is an explosion breccia. The presence of the tuff substantiates this, but the size of the blocks makes it difficult to conceive the magnitude of the forces required to move them intact. E. S. Moore,[5] in a recent paper, suggests that the Trout Creek conglomerate, which overlies the micropegmatite in the Sudbury Basin, is really an agglomerate. If this is true, it may be that the Geneva Lake breccia represents an orifice for this material, since it is only eight miles from the northwest rim of the Basin, and the breccia may extend nearer; it was not traced to its limits.

Granite-Syenite Injections.—The oldest intrusion into the Serpent formation is a medium- to coarse-grained granite that has syenitic phases. These intrusive masses are roughly lenticular in form and vary in width from a few feet to twenty or thirty and in length range from ten to several hundred feet; they occur scattered at intervals throughout the sediments. In places they follow the stratification and show an almost insensible gradation into the intruded sediments, causing little if any deformation of the bedding.

[5] E. S. Moore, Canadian Min. and Met. Bull. 215, pp. 351–61.

In the hand specimen they are dark to medium-colored, showing large amounts of hornblende, feldspar and minor amounts of quartz.

Microscopically, they consist of feldspar, chiefly microcline, albite, and orthoclase, the last two showing some alteration to sericite. The microcline is always fresh and seems to have crystallized later than the other feldspars; its resistance to alteration may be due to its tendency to resist fracturing on account of the cross-twinning. A few of the orthoclase crystals show intergrowths of quartz but this is not common. The hornblende that occurs is commonly unaltered but some of it has changed to biotite and chlorite. Calcite occurs in blebs and in veinlets and is a later introduction. Small crystals of apatite and large crystals of titanite are common accessory minerals.

Quartz may be a common constituent, but in places is so subordinate that the rock could be more properly termed a syenite. The granite and syenite may possibly represent two separate intrusions but are here considered as one. The intrusion close to the vein shows a sprinkling of later sulphides, chiefly pyrite and galena.

Alaskite.—There are a number of roughly lenticular intrusions of alaskite, similar in occurrence to the granite-syenite intrusions. They range from medium to coarse-grained or porphyritic in texture. In width they vary from a few feet to thirty or forty feet and their length may be several hundred feet.

In the hand specimen the alaskite has a younger and fresher appearance than the granite-syenite, and small flakes of chlorite are the only iron-bearing minerals.

Underground work discloses a close association between ore and alaskite, and superficially there appears to be a gradation from ore to alaskite. However, close examination shows that this gradation is due to the ore filling minute fractures in the latter.

Microscopically, the alaskite is composed chiefly of feldspar that ranges from microcline and orthoclase to albite and oligoclase. The first feldspars to crystallize were large in size and chiefly orthoclase and albite. These were then partly resorbed; later a finer-grained feldspar crystallized, which is chiefly microcline

although albite and orthoclase are also common. The larger and apparently older feldspars show the most alteration (chiefly sericitization), and the microcline shows much less alteration than the other feldspars.

The quartz is of two ages, viz: (1) Fine-grained material that crystallized with the finer-grained feldspar. (2) Fillings of fractures in the alaskite. The latter is a fine-grained quartz that may have accompanied the metallizing solutions. Calcite is also found with the feldspar and as veins that traverse it, and the probability is that it also accompanied the later quartz and sulphides.

The chlorite is a constant but minor constituent. It is a unique type showing abnormal Berlin blue interference colors. Similar material is found in the country rock and it is believed that it is not an original constituent of the alaskite.

A few sections show minor amounts of epidote, biotite and muscovite, but it is believed that the injections themselves were acidic, and that these minor minerals are residual and resulted from the assimilation of country rock, since they are found in abundance in it.

A common field name for this rock in the district is micropegmatite. Petrographic work shows no intergrowths of quartz and feldspar, so that the term alaskite is more logical, since the feldspar is chiefly alkaline and the texture is variable although usually coarse-grained.

That the alaskite was of a very fluid nature is evidenced by its spreading out along the bedding with little deformation of the strata. Even in thin sections it may be seen that quartz and feldspar have been introduced along the fine laminæ parallel to the bedding, whereas other bands of detrital material have not been disturbed. Additional evidence of its aqueous nature is suggested by the lack of a marginal phase where the alaskite abuts the intruded rock. There is no textural or compositional difference between the border phases and the interior portions of the alaskite and in this respect it is similar to many pegmatites.

Pre-mineral Diabase.—Diabase dikes of two ages have been recognized; the older is earlier than the ore. The pre-mineral dikes are tabular masses that dip from eighty degrees to vertical.

and range up to several hundred feet in thickness. Their strike is irregular and they commonly cut across the sediments.

One of these older dikes has been found on the 235 foot level where it intercepts the vein at an acute angle. In contact with the vein it is brecciated and contains veinlets of sulphides in non-commercial quantities. This same dike has been cut by several of the diamond drill holes and indications are that it is at least 120 feet wide, but it branches, since one hole shows included bands of sediments. Three separate dikes have been intersected by another drill hole.

In texture, these dikes range from fine to medium-grained, and although commonly massive, they may show slight schistosity.

Microscopically, they exhibit intense propylitic alteration. The most abundant mineral is hornblende, which occurs in crystals that are commonly twinned and have probably formed from original pyroxene; it is of variable composition, some of it being decidedly sodic. Biotite, chlorite, and magnetite are present.

The feldspars range around andesine-oligoclase, and most of them have been intensely altered with the development of secondary mica, epidote, zoisite, and calcite, so that in many cases only the original outline of the feldspar crystal remains. Intergrowths of quartz with the feldspars are common, and in all cases the feldspar is highly altered, suggesting that the quartz has been derived from the breakdown of the feldspar. Some later quartz has also been introduced as veinlets, in the vicinity of the ore.

Magnetite and ilmenite are scant. Titanite is a common constituent of all the pre-mineral dikes and it is commonly fine-grained, which gives it an isotropic appearance. Pyrite, apatite and leucoxene are present in minor amounts. Calcite occurs in small masses from the alteration of the feldspars but is also found in veinlets wherever the diabase is in close proximity to the ore.

A pre-mineral diabase dike cuts the alaskite on the surface and is, therefore, younger, even though it is considerably more altered than the alaskite.

Post-mineral Olivine Diabase.—Underground work has exposed another dike that intersects the ore and this is apparently post-mineral. Similar dikes have been found in two of the drill holes,

one of which is apparently the continuation of the ore found underground (Fig. 1).

In the hand specimen there is an observable difference between the dikes of the two ages. The younger ones are blacker in color,

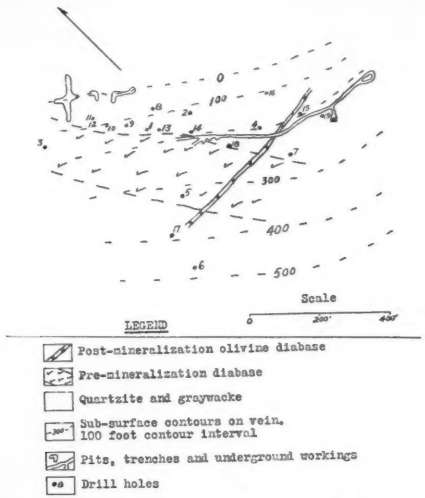

FIG. 1. Plan view of vein (expressed by contours), and its relation to the pre- and post-mineralization dikes, as obtained from drill hole data and underground development work. Where the vein intersects the pre-mineralization dike, it is not of economic value.

finer-grained and less altered. Also, they show no schistosity and attain a maximum thickness of only ten feet.

Microscopically, the chief constituents are lath-shaped crystals of plagioclase that range from labradorite to andesine and have a marked diabasic texture. The feldspars are only slightly altered, chiefly to small flakes of scapolite and minor amounts of mica.

Considerable olivine is present and is characteristic of the post-mineral dikes; most of it has been altered to serpentine. Magnetite is abundant as an original constituent and also as an alteration product of the olivine. Minor amounts of augite, biotite, chlorite, and calcite are present, the last three as secondary minerals.

Microscopically, the later diabases can be distinguished from the pre-mineral dikes by the following features: (1) basic plagioclase, chiefly labradorite; (2) large amounts of olivine and its alteration product serpentine; (3) absence of titanite; (4) much primary magnetite; and (5), slight alteration. Both of these dikes may represent differentiates of large gabbro and norite intrusions that occur in the area.

STRUCTURE.

The region is characterized by folds that strike northeasterly and dip from 30° to 75°. This structure finds expression in the topography in the form of prominent ridges that are composed of the more resistant formations. Considerable faulting has also taken place. In general the faults are normal, and cut the folds at an acute angle. In places the sediments have been dropped into the older granite as, for example, at the southeast corner of Geneva Lake, where the Espanola limestone lies within pre-Huronian granite. Quirke[6] has indicated this faulting and believes that there has also been considerable faulting parallel to the folds, as shown by the repetition of formations and lines of intrusion.

In the vicinity of the mine, the structure is relatively simple. The formations dip about 45° southwesterly and south; the strike is generally northwesterly but an easterly and northeasterly swing south of the shaft indicates that the property is located on the southeast flank of an anticline and that small variations in strike are due to cross folds. The few drag folds that have been found substantiate this and, in addition, seem to indicate that the fold is plunging slightly to the northwest.

ORE DEPOSITS.

The ore body consists of an irregular tabular vein within graywackes and quartzites that contain injections of granite and alaskite. The strike and dip of the vein conform, in general, to the sediments. The width varies from two to nine feet with an

[6] T. T. Quirke, *op. cit.*

average of about five feet. The walls may be sharp but commonly the massive ore grades into barren country rock within a distance of two feet.

The ore is mostly massive but commonly there are bands which are due to aligned inclusions of country rock, and also to ribbons of sphalerite, pyrite and galena, both of which parallel the bedding. The bands of country rock in the ore may grade into barren wall rock.

The 235 foot level is the deepest underground working. However, one drill hole cut five feet of ore at a vertical depth of 350 feet, and indicates that the ore continues on the south side of the slightly mineralized pre-mineral dike (Fig. 2). This dike is

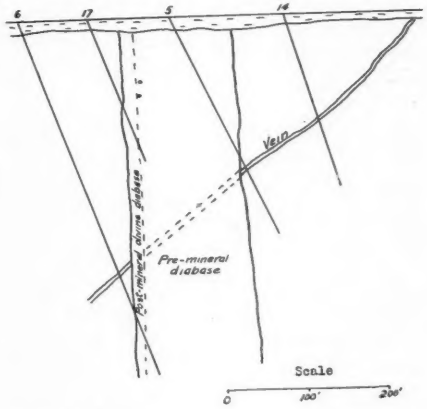

FIG. 2. Vertical section through drill holes 6, 17, 5 and 14. Showing position of the vein in respect to the pre-mineral diabase and the post-mineral olivine diabase. Pre-mineral diabase contains only small stringers of sulphides and some lenses of country rock. The vein parallels the country rock, which is chiefly quartzite and graywacke.

brecciated and is cemented with quartz that is thought to have been introduced with the ore solutions.

The vein also cuts several alaskite masses, one of which, near the pre-mineral diabase, is about fifteen feet in width, and ap-

parently grades from alaskite into ore and then in turn into the quartz that cements the brecciated margin of the diabase dike. The change occurs within a distance of four or five feet, but close examination shows that the ore fills fractures in the alaskite and that it is not differentiation *in situ*.

Mineralogy.—The mineralogy of the deposit is exceedingly simple. Sphalerite, a dark variety apparently high in iron, is the most abundant metallic mineral. In general, it occurs in flakes that range in size from .05 mm. to 2 mm. and forms the main body of the ore. Galena, which is next in abundance, occurs in small flakes ranging in size from .01 mm. to 1 mm. It is commonly associated with the wall rock inclusions, particularly with the chlorite, which may have favored its deposition. Pyrite is abundant; in places it predominates. It occurs in crystals from .02 mm. to 2 mm. in size. Chalcopyrite and pyrrhotite occur in negligible amounts but both are invariably associated with the more quartzose portions of the vein, particularly close to, or filling, fractures in the alaskite. The chalcopyrite is fine-grained and disseminated but the pyrrhotite occurs in masses and veinlets that cut other sulphides.

Non-metallic Minerals.—Non-metallic gangue minerals are abundant and consist of chlorite, quartz, epidote, biotite, feldspar, hornblende, muscovite, calcite, diopside and garnet. The chlorite is in small flakes that represent unreplaced material from the country rock, as the surrounding graywacke shows much of it.

The hornblende, epidote and mica also represent residual material from the country rock. The mica commonly occurs as fresh flakes with undistorted laminæ although imbedded in the sulphides. Thin sections show that the sulphides replace and occupy fractures in the above minerals.

Detrital quartz and feldspar are common. This quartz is in rounded grains that are commonly surrounded by sulphides, and the vein quartz is in blebs and veins. The feldspar apparently is derived from country rock that has resisted replacement. It is cut by sulphides, considerably altered, or replaced by irregular residuals (Fig.3). Calcite, in small veins and blebs throughout the ore, has been introduced with the sulphides; some rhombs with

faces two to three inches across have been found. A few specimens show microscopic particles of grossularite and diopside which are fractured and traversed by sulphides.

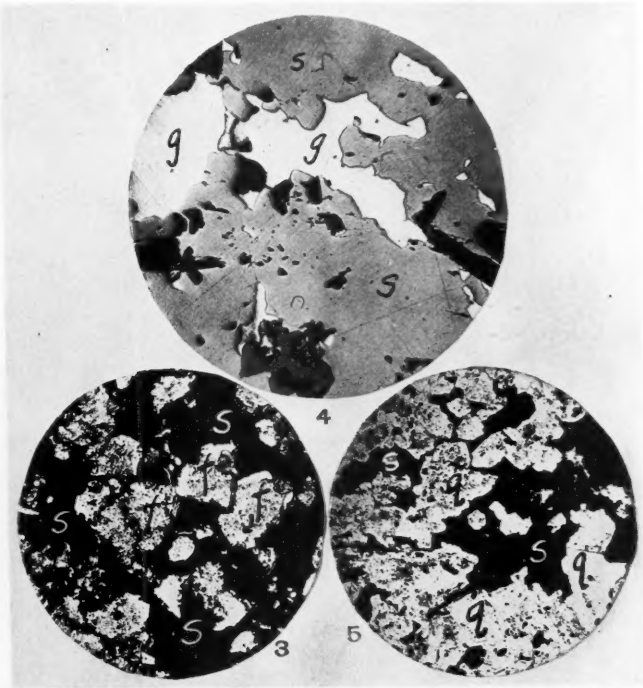

FIG. 3. Sericitized feldspar (*f*), being replaced by sphalerite (*s*). Plain polarized light, × 28.

FIG. 4. Polished section showing usual relationships of sphalerite (*s*) and galena (*g*). × 28.

FIG. 5. Sphalerite (*s*) entering fractures and replacing arkosic quartzite (*q*). Plain polarized light, × 28.

In summary, the non-metallic gangue minerals are earlier than the sulphides and have been replaced to a considerable extent by

them. A number of them, such as chlorite, hornblende, mica, quartz, feldspar, and epidote, are residual minerals from the sediments, and others, such as quartz, calcite, diopside, and garnet, were deposited from the ore-bearing solutions.

Paragenesis.—Examination of polished and thin sections shows the following general relationships: pyrite was the first to crystallize and continued late in the deposition, overlapping some of the other sulphides. It was followed successively by sphalerite, galena, chalcopyrite and pyrrhotite. The early crystallization of the pyrite is shown by: (1) the euhedral form; (2) veinlets of sphalerite that cut the pyrite; and (3), sphalerite and galena that mold themselves around the pyrite crystals.

The sphalerite-galena relations are difficult to determine, since their age relations are close; in part, they are contemporaneous. In general, the galena is later than the sphalerite, but sphalerite later than galena was not observed. Some galena, in veinlets, clearly cuts across the sphalerite; one large specimen of banded pyrite, sphalerite, and country rock, shows transverse fractures filled with later galena.

It is worthy of note that in all the specimens that contain galena and sphalerite, the galena exhibits concave surfaces towards the sphalerite (Fig. 4). Some authors cite this relationship to indicate that the sphalerite has replaced the galena, but the evidence of the galena veinlets and the tension fractures in the sphalerite filled with galena is more decisive. In view of this, it seems that solution boundaries can be used only with the greatest caution in determining paragenesis and as criteria of replacement.

Chalcopyrite succeeds galena in the order of deposition. The small amount of the mineral present in the ore and its occurrence in the more quartzose portions of the vein make its position open to some doubt, but commonly it is closely associated with flakes of galena and molds itself around them.

Pyrrhotite was the last sulphide to crystallize; underground, small veins, up to one inch in width, clearly cut across all the ore minerals. Apparent massive pyrrhotite veinlets in the hand specimen, are shown in polished sections to be blebs and small veinlets in galena and sphalerite. It might be argued that these pyrrhotite

blebs are residual, having been left by the incomplete replacement of the pyrrhotite by the sphalerite.

Galena-Sphalerite Relations.—The galena-sphalerite relations described above seem to hold almost invariably in all lead-zinc deposits that are clearly connected with igneous activity. Specimens of galena-sphalerite from a number of localities have been examined, and the usual order is that galena is later than sphalerite. It is true that in many cases they appear to be contemporaneous, but sphalerite later than galena was not observed from deposits of intermediate to high temperature type. This order is not the invariable rule in the shallow deposits of the Mississippi Valley field, where in many cases galena precedes sphalerite, or there may be several periods of both sphalerite and galena. This reversal found in the shallow vein-zone may be due to concentration, that is, the solutions may be saturated in respect to sphalerite and undersaturated in galena.

The fact that sphalerite does crystallize before galena in intermediate to high temperature deposits would indicate that it is a temperature phenomenon. This is borne out by the zonal distribution observed in many deposits, indicating that, in general, sphalerite crystallizes at a higher temperature than galena.

This temperature distribution suggests that in lead-zinc deposits there may be a decrease in lead tenor in depth, and an increase in zinc, as has been proved in a number of cases. In some instances, the vertical range at which this takes place is great; in other cases it might occur within a short distance. Furthermore, some deposits show that, in general, the galena is later, but in other deposits, simultaneous crystallization is usual, although the lead and the zinc content may be the same in both cases. It is believed that both of these phenomena are dependent to a great extent on the rate of crystallization or, in other words, the speed of cooling; although factors such as concentration, rate of entrance of ore solutions, or wall rock, may play important parts.

If in a given galena-sphalerite solution the sphalerite begins to crystallize first, then if the cooling is relatively rapid, the time interval between the crystallization of the galena and the sphalerite is relatively short and would give rise to contemporaneous inter-

growths of the two, with little reaction (replacement) between them. Particles of galena would be caught in the sphalerite or vice versa. If the cooling were relatively slow, the time interval would allow for the fractionation of the galena solutions from the crystallizing sphalerite. This would give opportunity for reaction between the galena solutions and the crystallized sphalerite, and evidence of replacement of the sphalerite by the galena or of veins of galena cutting the sphalerite would be seen. If the factors were such that galena crystallized first, the principle would still apply.

The rate of cooling would be controlled by the following factors: (1) Size of intrusion which brought in the ore solutions, (2) temperature of the intruded rock, (3) depth below surface. and (4) type of country rock. It seems possible in some cases that rapid cooling would mean that there might be a quick vertical or horizontal change in the mineral constituents of the ore, or in the tenor of the ore.

Osborne[7] describes a contact diabase deposit in a township adjacent to the Geneva Lake deposit. Here, he finds zones of magnetite, pyrite-chalcopyrite, galena-sphalerite and cobalt, all within a distance of a few hundred feet of the intrusive. He states that the paragenetic relations between the galena and sphalerite could not be obtained on account of this telescoped zoning. In the Geneva Lake deposit, which probably owes its origin to diabasic intrusions, cooling has been somewhat slower, so that in places the galena has crystallized later.

Schofield,[8] in describing the Sullivan Mine, finds that massive galena occurs in lenses in the center of the vein. On either side of the galena lens is a galena-sphalerite zone and farther out, sphalerite, pyrrhotite and garnet on the walls. It appears that this arrangement is also a cooling phenomenon. On the walls where the solutions cooled quickly the higher temperature minerals crystallized. In the middle of the vein, cooling was slower and the galena separated out from the other minerals.

Tenor of the Ores.—The average tenor of the ore is: $.40 gold;

[7] F. F. Osborne, ECON. GEOL., vol. 24, pp. 722–32, 1929.

[8] S. J. Schofield, Canada Dept. of Mines, Memoir 76, pp. 132.

2.3 ounces of silver; 4.5 per cent. lead; and 11 per cent zinc. In general, there is a three to one ratio of zinc to lead regardless of the width of the vein and the metallic content or the location in the vein, although locally there may be slight variations from this ratio. This uniform ratio of lead to zinc is indicative that they have been deposited from the same solutions and that where there is a later crystallization of galena it is due to temperature conditions.

The silver ratios vary, seeming to indicate that it may be with either the galena or the sphalerite. No silver minerals were recognized; possibly the silver is in solid solution in both the galena and sphalerite. The spectroscope shows the presence of silver in both the crystalline sphalerite and galena.

On the surface, some free gold and silver were found in quartz stringers. It is probable that this mineralization is not of the same period as the lead-zinc as none has been found in the ore itself. It may be that the free gold and silver had their origin with the alaskite.

Genesis.—It seems quite evident that the ores have been deposited from aqueous solutions, fractionates of some intrusion in the region; but as to their exact nature, their temperatures, and their source there is some uncertainty.

Some of the gangue minerals such as grossularite and diopside are indicative of relatively high temperatures and these minerals probably originated with the ore, since they are found only in the vein. Pyrrhotite is commonly associated with high temperature deposits but in this case it has crystallized later than the ore minerals. This may be due to a small concentration or a later introduction. The general structure of the vein, the dense compact texture of the ore, and the lack of druses and vugs, further substantiate the possibility that the deposit is an intermediate to high temperature ore.

The general structure of the vein, that is its conformity with the bedding of the sediments; the banding of the ore, conforming with the structure of the wall rock; the intimate association with the ore of minerals such as chlorite, detrital quartz and feldspar, and hornblende, all of which are original constituents of the wall

rock; the gradation of massive ore into country rock in many places; the existence of bands of sediments in the ore mass with a structure corresponding with that of the wall rock; and the microscopic work; all indicate that replacement of the country rock by extremely mobile solutions was the dominating factor.

That in some cases fracturing existed, is shown in a few places where the vein cuts across the sediments for a few feet and then continues parallel to the bedding. The pre-mineral dike is also shattered at the point where the vein comes in contact with it. It is probable that the fractures served as channels of access for the ore solutions and that from these fractures they spread out and replaced the country rock. The paucity of sulphides in economic quantities in the pre-mineral dike, in contrast to the massive ore adjacent, is an interesting example of the influence of wall rock upon the precipitation of sulphides.

The nature of the solutions is indicated by the extremely fine banding. In thin sections, grains of sphalerite and galena can be seen wrapped around the detrital quartz and feldspar or in small stringers that parallel the stratification (Fig. 5). The gradation and dissemination of the sulphides would also point to the fact that the solutions were extremely mobile. High mobility would appear to indicate low viscosity. It may be that many ore veins are a result of highly viscous solutions but evidence here is against a solution of that nature.

Origin of the Solutions.—The most conspicuous feature underground is the close association of ore and alaskite. Close to the contact of the ore and the pre-mineral diabase, there appears to be a gradation from alaskite to sulphides to quartz that cements the brecciated margins of the dike. This gradation is over a distance of ten feet. At several places in the drift, and in some of the drill cores, the ore abuts the alaskite or is disseminated in it, suggesting that the ore is a differentiate of the alaskite.

It has been noted previously that a dike microscopically identical to the pre-mineral dike that occurs on the 235-foot level, cuts across an alaskite body that occurs on the surface and, therefore, the alaskite must pre-date the pre-mineral diabase.

F. F. Osborne [9] has noted a contact diabase deposit a few miles from the Geneva Lake property. From his description of the diabase, it is probable that it is closely akin to those found in this region. The deposit that he describes also contains galena and sphalerite.

Further evidence that the diabases of this region have carried sphalerite is found in the southeast corner of Geneva Lake where there is a contact deposit that is chiefly magnetite and specularite, but with a few flakes of sphalerite.

It is evident that the alaskite as a source of the ore must be eliminated. The presence of the pre- and post-mineral diabases, the proximity of larger basic masses, and the fact that the diabases have carried lead and zinc, indicate that in all probability the Geneva Lake deposit has been derived from a basic magma.

ACKNOWLEDGMENTS.

I wish to extend thanks to The Lake Geneva Mining Co. Ltd. for their consent to the publication of this report, and to Mr. W. E. Bawden for his information and hospitality; also to Wright, Boydell, James, and Associates, mining engineers and geologists of Toronto, Canada, for first offering the opportunity of visiting the area; and to Drs. Ries, Gill and Nevin, of Cornell University, for their kind and constructive criticism.

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[9] F. F. Osborne, *op. cit.*, note 3.

"RED BED" COPPER DEPOSITS IN NOVA SCOTIA AND NEW BRUNSWICK.

E. B. PAPENFUS.

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INTRODUCTION.

THE copper deposits of Wentworth Centre, in Cumberland County, Nova Scotia, and Dorchester, New Brunswick, are analogous to the metallized "Red Beds" of the southwestern United States. This paper gives a detailed description of the ores from these two localities and offers a possible mode of genesis. For comparison a description of a similar deposit in Turkestan is appended.

This "Red Bed" type of deposit is widely distributed; there are occurrences in England, Russian Turkestan, Russia, and Germany, as well as those in the "Red Beds" of Colorado, Oklahoma, Texas, New Mexico, Idaho, Utah and Arizona.

The most distinctive characteristics of the "Red Bed" type of ore are:

(1) The occurrence of the ores in sedimentary rocks of

Carboniferous, Permian, Triassic, or Jurassic age, such as sandstone, shale, or arkose, which are not necessarily of red color and are generally far removed from igneous rocks.

(2) The frequent association of the ore with plant remains that have turned to coal and have been partly replaced by the ore minerals.

(3) The occurrence of the ore as nodules and concretions, or replacements of the cementing material of sandstones.

The principal ore minerals are pyrite and chalcocite together with their oxidation products; chalcopyrite and bornite have been found in a few places.

GENERAL GEOLOGY.

The deposits of Dorchester, New Brunswick, are in rocks of Middle Carboniferous [1] age and the copper ore occurs in the lower part of the Millstone Grit formation.

The ore-bearing sediment proves to be a graywacke made up of quartz, orthoclase and plagioclase feldspars, and fragments of other rocks. The feldspars are much altered to kaolin. No calcite cementing material is visible, and the hand specimens are friable.

In Cumberland County, Nova Scotia, the best known occurrence is at Wentworth Centre. The rocks here are sandstones and shales of Permian [2] age. The ore-bearing rock is a graywacke similar to that from Dorchester.

It will be noted that the age of the copper-bearing rocks in Cumberland County is Permian, and in Dorchester Middle Carboniferous. This difference in age does not appear to have any genetic significance because it is probable that copper would be precipitated from solution in any rocks, irrespective of age, in which suitable precipitating agents and conditions existed. Thus it is reasonable to assign the same origin to both these deposits on the grounds of their proximity to each other and the similarity of their minerals and mineral relations.

[1] Ells, R. W., "Geology and Mineral Resources of New Brunswick," Report Geol. Surv. of Canada, 1907, pp. 89–90.

[2] Fletcher, H., Geol. Surv. of Canada, Ann. Report, Part P, 1890–1891, pp. 185–186. Fletcher, H., Geol. Surv. of Canada, Summary Report, 1902, p. 396.

MICROSCOPIC EXAMINATION OF THE ORE MINERALS.

The polished sections examined from Cumberland County and Dorchester are of three different types:

(*a*) Nodules and concretions of chalcocite and pyrite.
(*b*) Chalcocite and pyrite associated with carbonaceous matter.
(*c*) Chalcocite replacements of sandstone cementing material.

In many respects the three types are similar, as they show the same mineral relations. The ores of type *b*, however, always assume the elongated form and fibrous structure of a tree trunk, twig, or other fragment of wood.

Nodules and Concretions.

These vary in diameter in the specimens examined from about 1 to 2 inches (Fig. 1). The shape is generally slightly ovoid but some are almost spherical. All specimens are traversed by characteristic shrinkage cracks. The only minerals present in the concretions are quartz, pyrite, chalcocite, and covellite; the surface is commonly coated with malachite.

Quartz.—This occurs exclusively as small rounded grains averaging about 0.1 mm. in size, distributed evenly throughout the concretion. These grains occur embedded in both the pyrite and the chalcocite, but they are sparse. They are undoubtedly detrital grains of the original sediment in which the concretion grew. In one grain, convincing evidence of direct replacement of the quartz by chalcocite was found, but no similar structure by pyrite could be seen.

Pyrite.—This mineral is fairly plentiful in the nodules and occurs chiefly around the outer rim, extending inwards from 5–10 mm. Small amounts are also scattered in the center of the nodule.

The bulk of the pyrite occurs in elongated masses that radiate towards the periphery of the concretion (Fig. 1) and are cut by innumerable veinlets of chalcocite. It is the radial orientation of these replacement veins of chalcocite that accentuates the radial structure of the pyrite.

The pyrite is undoubtedly residual and is in the process of being totally replaced by the chalcocite from the center outwards. It is probable that these concretions were once solid pyrite with a few detrital sand grains, this type being of fairly common occurrence elsewhere.

Chalcocite and Covellite.—The chalcocite is by far the most ab ndant mineral in the section. It predominates in the

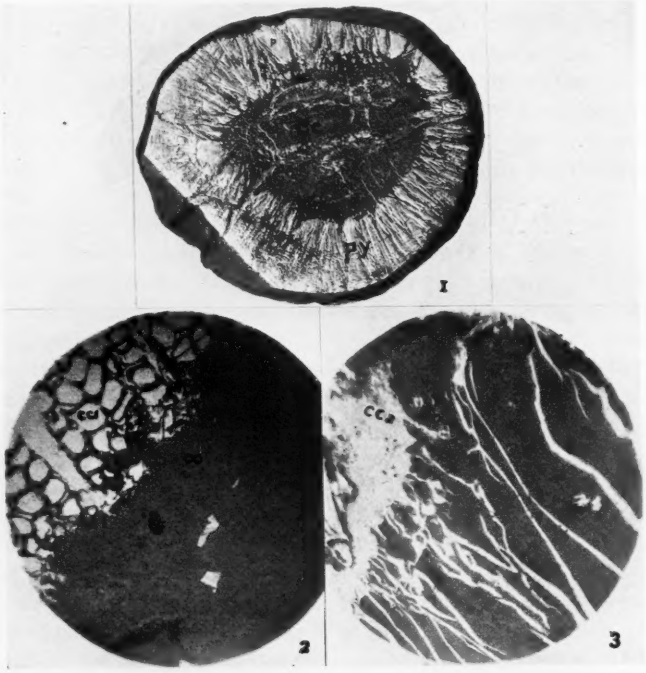

FIG. 1. Chalcocite-pyrite concretion from Wentworth Centre, Cumberland Co., Nova Scotia, showing radial pyrite (light) (*py*) round the outer zone with a core of chalcocite (*cc*) that is replacing pyrite. × 1½.

FIG. 2. Shows coal (*co*) and the first generation of chalcocite (*cc*1) that replaced wood before it turned to coal. × 140.

FIG. 3. Chalcocite (*cc*2) replacing coal (*co*) directly. × 140.

center and occurs along with a few detrital quartz grains and small amounts of residual pyrite. Around the periphery of the concretion, however, it is subordinate to pyrite.

The chalcocite has a bluish tinge and numerous small areas of covellite can be distinguished in it by means of differential etching with potassium cyanide or by means of the polarizing reflecting microscope.

As is usually the case, the covellite is later than the chalcocite, which in turn replaces both the quartz and the pyrite. The replacement of pyrite by chalcocite first started along the quartz-pyrite boundaries.

Paragenesis.—The paragenesis of this type of ore is simple and is briefly: detrital quartz (oldest), pyrite concretion, chalcocite, covellite.

Chalcocite and Pyrite Associated with Carbonaceous Matter.

These ores are replacements of plant remains and in external form resemble fossils of the plant from which they are derived and show the fibrous and cellular structure of wood. The minerals present are coal, pyrite, chalcocite and covellite.

Coal.—This is fairly abundant and is obviously the earliest constituent. Under the microscope it is a uniformly neutral gray color and takes a fine polish. It is replaced directly by chalcocite, which cuts it in innumerable small veins (Fig. 3).

Slight etching of the chalcocite in the vicinity of a coal fragment brings out very clearly a definite cell structure of wood (Fig. 2). The etching is best done by holding a drop of nitric acid on a platinum wire above the portion to be etched without allowing the liquid to touch the section. This brings out the cell structure without destroying the polish of the section. The outlines of the cells are probably due to residues of carbon that represent portions of the original wood that were most resistant to decomposition and replacement. Such portions are the celluloses and lignins, and it is from these that all coal is derived and it is these also that form the cell walls of ordinary wood. Hence, it may be concluded that the iron and copper solutions advanced along channels

in the cellulose and lignocellulose, replacing as they went the gums, resins, and other substances less resistant to the decomposition processes of bacteria and fungi. By this means the cells of the wood would become filled by pyrite and chalcocite. The fact that the cell structure is retained indicates that the wood was impregnated with pyrite and chalcocite before it became carbonized to coal.

There are also present in the sections, however, fragments of true coal which have undoubtedly been replaced directly by chalcocite (Fig. 3). In these cases carbonization must have been completed before replacement took place, and such pieces of coal must have been composed entirely of material resistant to decay. The exines of many spores [3] found in coals resist decay in this way, and it is likely that the true coal found in these sections is remnants of spores, parts of which have already been replaced by chalcocite.

Pyrite.—Pyrite occurs in all these ores in fairly large quantities, and has a characteristic granular appearance, the interstices between the grains being in all cases filled with chalcocite that replaces it along the borders of these grains.

In practically every instance the pyrite retains the cellular and fibrous structure of the wood which it must have replaced (Fig. 4). This was shown clearly by polishing a specimen in two planes at right angles to each other, one plane being approximately parallel to the grain of the fossil wood and the other across it. The parallel section shows the pyrite in fairly regular elongated lenses, whereas the section at right angles shows clearly the typical cell structure formed from grains of pyrite (Fig. 4). Thus the pyrite must have replaced the wood during the decomposition of the cell material.

Pyrite was not found to replace coal directly; hence it is probable that the pyrite mineralization did not continue until the spores and cell walls were carbonized to coal.

Chalcocite and Covellite.—Chalcocite is by far the most abundant mineral in these ores and occurs associated with covellite. Chalcocite fills the sap tubes of the wood as shown

[3] Thiessen, R., Bull. 117, U. S. Bureau of Mines, 1920, p. 18.

in a section (Fig. 5) cut at right angles to them. In some sections a color distinction in the chalcocite can be seen; some of it has a bluish tinge whereas other areas are composed of the normal white variety. An etch of the two varieties with potassium cyanide brings out a definite wood-cell structure in the case of the blue chalcocite, but the white variety shows no such structure. This leads to the conclusion that the chalcocite is of two generations; the first was introduced while the wood was uncarbonized and still retained its cell structure, and the second, which replaces coal directly, is found cutting the first generation and has removed almost all traces of cell structure shown by the first generation. This can be seen in Fig. 5, where the veins of chalcocite that cut the coal can commonly be traced through areas of chalcocite that show cell structure; in these cases the veins of the second generation obliterate almost all traces of the cells. The second generation of chalcocite contains no covellite.

So far as is known there is no second generation of pyrite corresponding to the second chalcocite generation, since no direct replacement of coal by pyrite has been observed.

Unidentified Mineral.—In one specimen of the Cumberland County ores that contains residual coal and chalcocite showing cell structure, a yellow mineral occurs that resembles pyrite in color but has less relief and is considerably softer. Its physical and etch properties do not correspond with any of the minerals listed in the Davy-Farnham tables. The mineral is closely intergrown with chalcocite and grades imperceptibly into it. In some places the unknown mineral forms a cell structure with the chalcocite, which appears to be replacing it.

As the mineral is so closely intergrown with chalcocite and occurs in such small quantities, it is impossible to obtain pure particles and an admixture of impurity may account for several of its etch reactions. For this reason no chemical analysis of the mineral was made. However, a very similar mineral has been found in the oxidized zone of the ores of

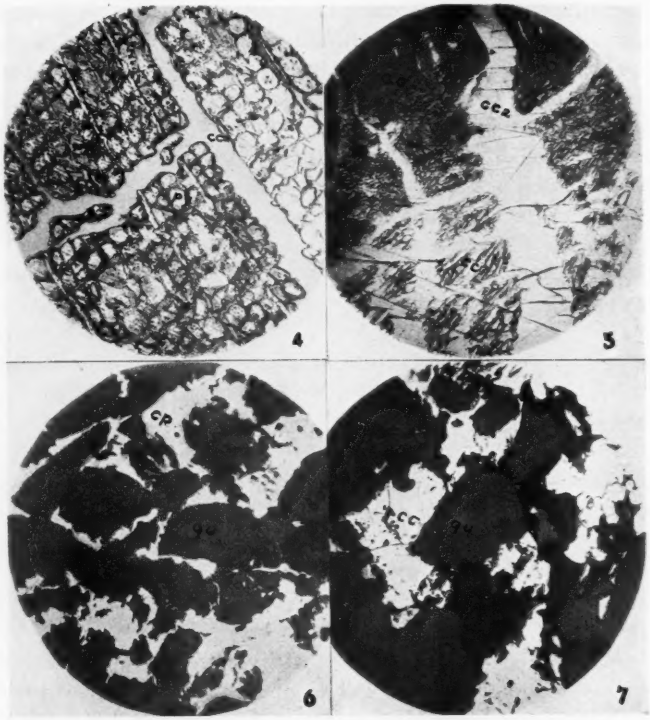

FIG. 4. Section cut at right angles to the cell structure. Pyrite (*py*) shows cell structure and is cut by chalcocite (*cc2*) in large and small veinlets. × 65.

FIG. 5. Shows second generation chalcocite (*cc2*) replacing coal (*co*) directly and obliterating almost all cell structure shown by the first generation of chalcocite (*cc1*), which replaced the wood before it was carbonized to coal. × 65.

FIG. 6. From Djez Kazgan, Russian Turkestan. Chalcopyrite (*cp*) replacing detrital quartz (*qu*). Chalcopyrite has also replaced cementing material of sandstone. × 65.

FIG. 7. Chalcocite (*cc*) which has replaced all the cementing material of a sandstone leaving only detrital grains of quartz (*qu*). Cumberland Co., Nova Scotia. × 65.

Tezuitlan, Vera Cruz, and is being investigated in the laboratory of the Massachusetts Institute of Technology.

Properties.—As closely as could be ascertained the properties of the mineral are: color, light yellow similar to pyrite; hardness 3–3.5, hence relief is about the same as the surrounding chalcocite, fairly sectile; magnetism is slight, not so great as pyrrhotite.

Etch Properties.—The mineral gives a negative reaction to all Davy-Farnham reagents.

Microchemical tests indicate the presence of iron and copper.

Paragenesis.—The paragenesis of this type of ore is: coal and fossil wood (oldest), pyrite, unknown mineral, chalcocite, covellite, chalcocite (second generation).

Chalcocite Replacements of Sandstone Cementing Material.

These ores bear a strong resemblance as far as the mineral relationships are concerned to the pyrite-chalcocite concretions. The replacement structures, however, are somewhat different (Fig. 7), and the characteristic nodular form is lacking. The constituent minerals are quartz, pyrite, and chalcocite. No coal or fossil wood is present.

Quartz.—The quartz is undoubtedly detrital grains of sandstone. This can be seen by the general rounded appearance of the grains, their spacing, and their haphazard orientation, all of which are characteristic of an ordinary sandstone. The grains are not scattered evenly throughout the section; there is a gradation from areas with numerous closely-spaced grains, as is the case with an ordinary sandstone, to areas where quartz grains are few in number and in general comparatively far apart. Many of the grains are veined by chalcocite, and some are replaced by this mineral to such an extent that only skeletons remain.

Pyrite.—Pyrite is rare in this type of ore, probably having been mostly replaced by chalcocite, which cuts through the pyrite grains in small veinlets. Thus, the occurrence of the

pyrite is in somewhat scattered masses full of embayments of chalcocite. The pyrite is undoubtedly later than the quartz.

Chalcocite.—This mineral is abundant; it appears to be quite homogeneous and apparently contains no covellite. In appearance and structure it resembles the chalcocite of the nodules and concretions. This mineral has completely replaced the original cement of the sandstone (Fig. 7) and pyrite; even quartz grains are being attacked.

Paragenesis.—The pyrite was introduced into the sandstone, replacing probably both the quartz grains and the cementing material. Chalcocite was next precipitated, replacing (1) the sandstone cementing material, (2) the quartz grains, (3) pyrite.

Summary.

The foregoing descriptions of the three types of ore which are found both in Cumberland County and at Dorchester indicate that in each type the same ore minerals occur, and these bear the same relation to each other, the one exception being the absence of carbonaceous material and its accompanying wood structure in the nodular and sandstone ores. Thus it is concluded that the three types were formed by identical solutions, though the precipitating agents in each case may have been different.

THE ORES OF DJEZ KAZGAN IN THE KHIRGIZ STEPPES OF RUSSIAN TURKESTAN.

General Description.—An examination of polished sections of ores from these deposits[4] was made for comparison with those of Cumberland County and Dorchester.

No replacements of fossil wood or coal are mentioned from these occurrences and the structures of all the specimens examined bear a strong resemblance to the chalcocite replacement of sandstone cementing material which is so common in the Nova Scotia and New Brunswick occurrences. The ore minerals, however, are quite different, and the speci-

[4] J. Mackintosh Bell, "The Spasski and Atbasar Copper Mines in Siberia," *Min. & Sci. Press*, May 22, June 5, 1920.

mens examined contain quartz, chalcopyrite, bornite, chalcocite, covellite, and malachite. No pyrite is present. Some specimens contain chalcopyrite as the predominant ore mineral; in other cases bornite is predominant.

Microscopic Examination of the Ore Minerals.

Quartz.—This occurs in much the same way as in the ores of Nova Scotia and New Brunswick; in rounded grains having a similar shape and orientation to the grains of a sandstone. The quartz is obviously detrital and is undergoing replacement by either chalcopyrite or bornite.

Chalcopyrite.—This ore mineral may replace quartz directly. Where the chalcopyrite occurs abundantly it acts as a cement for the quartz grains and has undoubtedly replaced the original cementing material (Fig. 6). In sections where bornite is the principal mineral, the chalcopyrite occurs as small residuals veined by the bornite.

Bornite.—The occurrence of bornite is similar to the chalcopyrite. It also veins and replaces residuals of chalcopyrite.

Chalcocite and Covellite.—These two minerals are rare and occur as small veinlets and blebs replacing the bornite. No relations were observed between the chalcocite and covellite.

Summary.

The ores of Djez Kazgan differ from those of Nova Scotia and New Brunswick in the absence of fossil remains and in the constituent ore minerals. It is said, however, that typical replacements of carbonaceous matter [5] are found in the Kargalinsk Steppe in the Osenburg Province. This occurrence is not far north of Djez Kazgan.

This description of the Turkestan ores serves to show that, in apparently similar deposits elsewhere, chalcopyrite and bornite may form. It is recognized that the genesis of the Turkestan deposits is not definitely settled.

[5] A. Adiassewich, "A Journey to Central Asia," *Trans. Inst. Min.* and *Met.*, vol. 17, pp. 509–510, 1907–1908.

GENESIS OF THE "RED BED" COPPER DEPOSITS.

General Genetic Considerations.—A remarkable similarity exists between the various deposits of the "Red Bed" type, and with one or two doubtful exceptions the same mode of origin can be ascribed to all of them.

Although a deposition by ascending magmatic waters is not wholly excluded, the writer believes that a genesis by descending meteoric waters is the more likely explanation. The temperature of the mineralizing solutions must have been very low in order to replace plant remains without destroying the cell structures, and it is probable that they were similar to the solutions that are responsible for the secondary chalcocite enrichment zones of many of the important copper and silver deposits.

Source of Some of the Ores.—Hypogene ores of copper are commonly in the form of sulphides. On oxidation, these change to the soluble sulphates and travel in solution in this form.

It is, of course, difficult to trace the copper in these deposits back to its original source, but in the case of the "Red Bed" deposits of the Southwest the probable history is well summarized by Finch,[6] who assumes that the original copper came from pre-Cambrian rocks that were exposed to erosion at the beginning of the Triassic. He is of the opinion that there are two periods of redeposition; the first, during the Cretaceous, when the disseminated metals in solution in the Triassic and Jurassic sediments were precipitated by the hydrogen sulphide evolved in the formation of coal, and the second period, which took place from early Tertiary to the present day, when the copper-iron ores were once more exposed by uplift and erosion and deposited as oxidized ores in favorable places such as faces of cliffs and dip slopes.

In the case of the ores of Nova Scotia a possible source of the copper is from the Triassic lava flows, known as the North Mountain basalt,[7] which are exposed from Digby Neck

[6] J. W. Finch, "The Sedimentary Metalliferous Deposits of the Red Beds," *Am. Inst. Min. Eng.* Tech. Publ. 51, 1928.

[7] S. Powers, "The Acadian Triassic," *Jour. Geol.*, 24, pp. 262–268, 1916.

northeast for a distance of 120 miles along the west coast of Nova Scotia. The flows vary in thickness, the bottom one being the thickest (600 feet). Throughout their whole area they contain particles of disseminated native copper; probably chalcocite occurs as well. Though the present exposures of this rock are about 80 miles distant from Wentworth Centre, it is probable that at one time they had a much greater distribution, for the dip is only 8 degrees to the north. Hence it seems quite possible that these flows were the original source of the copper in the Wentworth Centre ores.

At St. John, New Brunswick, the Carboniferous [8] contains flows of amygdaloidal basic rocks, which may have been a source of the copper of the Dorchester deposits. There are also several copper deposits in pre-Cambrian [9] rocks along the shores of the Bay of Fundy; chalcopyrite is the chief ore mineral in these deposits, and the erosion of these ores may have supplied the metals of the Dorchester deposits.

Precipitation of the Ore Minerals.—The foregoing implies that the ore minerals were derived from hypogene sulphides, by processes of oxidation and weathering which converted the sulphides to soluble sulphates. The solutions thus formed seeped down through partially unconsolidated or pervious sediments and the metals were precipitated as sulphides, principally as pyrite and chalcocite.

Certain zones within the rocks were more favorable to precipitation than others, and it will be interesting here to investigate a few probable causes of precipitation. The ores occur in three ways, (1) as replacements of fossil wood and coal, (2) as nodules and concretions, (3) as replacements of the cementing material of sandstones. Apparently the same conditions prevailed in the case of the concretions and sandstone replacements, as their microscopic characteristics are very similar.

Ore Replacements of Fossil Wood and Coal.—In investigating

[8] "East. Quebec and the Maritime Provinces," Geol. Surv. of Canada, Guide Book No. 1, Pt. II., p. 370, 1913.

[9] R. W. Ells, "Geology and Mineral Resources of New Brunswick," Geol. Surv. of Canada, 1907, pp. 87–89.

any possible precipitating agents in the case of ore replacements of carbonaceous matter, it is necessary to know what was the condition of this material at the time of replacement. The microscopic examination of the ores from Nova Scotia and New Brunswick presents convincing evidence that replacement by the ore minerals took place both before the wood was changed to coal when the cell structure was still preserved, and after the wood had turned to coal. Ruth St. John [10] has shown that silicification of wood can take place along cellular channels leaving the cell walls unattacked, and this is probably what happened in the first generation of mineralization of the Nova Scotia and New Brunswick wood replacements. Thus a brief examination of the products of vegetable decomposition will perhaps help to clarify the mode of precipitation of these ores from their sulphate solutions.

The decomposition of wood [11] consists first in a simplification of the constituents from a greater to a lesser complexity, the final products of decomposition being water, ammonia, and carbon dioxide, in the presence of oxygen, and hydrogen and methane under anaërobic conditions. None of these compounds would have the effect of precipitating sulphides from sulphate solutions. During the decomposition of wood by bacteria, however, large quantities of organic acids and alcohols are produced, these being the end products of anaërobic metabolism. Clarke [12] draws attention to the "humus acids," which can act as reducing agents and thus might reduce sulphate solutions to the sulphide and cause precipitation of pyrite and chalcocite. Organic alcohols are also strong reducing agents and might also cause precipitation of these ore minerals.

A large part of the chalcocite was undoubtedly precipitated by the action of copper sulphate on pyrite according to well known reactions.

[10] Ruth N. St. John, "Replacement vs. Infiltration in Petrified Wood," ECON. GEOL., vol. 22, pp. 729–739, 1927.

[11] S. A. Wakeman and K. R. Stevens, "Processes Involved in the Decomposition of Wood . . . etc.," *Jour. Amer. Chem. Soc.*, vol. 51, pp. 1187–1196, 1929.

[12] F. W. Clarke, "Data of Geochemistry," U. S. Geol. Surv. Bull. 695, p. 479, 1920.

The direct replacement of coal by chalcocite is a more difficult problem. It was at one time thought [13] that precipitation of the sulphide in this case was brought about by the reducing action of the carbon in the coal according to the equation:

$$4CuSO_4 + 5C + 2H_2O = 2Cu_2S + 2H_2SO_4 + 5CO_2.$$

Experimental attempts by the writer to replace coal by chalcocite in this way were a failure. A polished surface of coal immersed in copper sulphate solutions under varying conditions was entirely unaffected after 50 days, and, moreover, no trace of evolved carbon dioxide could be detected. Carbon is known to be a very active reducing agent at the high temperatures of the blast furnace, but at the ordinary temperatures of meteoric conditions it is one of the most chemically inert substances known. Hence, the possibility of replacement being brought about directly by the reducing action of carbon may be dismissed.

Finch [14] thinks that hydrogen sulphide, given off during the process of formation of coal and retained in the rocks, is the essential precipitating agent, and he writes four chemical equations to illustrate this. This seems a probable explanation of the precipitation of the sulphides, but does not explain the replacement of coal by chalcocite (Fig. 3). In fact it is difficult to see how such replacement could take place at ordinary temperatures. It must be assumed that the coal was attacked and gave up some of its free carbon as methane, thus leaving room for replacement by chalcocite. Fig. 3 shows that the replacing solutions did not come in along the bedding of the coal but replaced it haphazardly in all directions.

Ore Concretions and Sandstone Cement Replacements.—These ores are undoubtedly derived from the same solutions as those that formed the pyrite and chalcocite replacements of coal and wood, but it is the writer's opinion that the precipitation

[13] W. Lindgren, U. S. Geol. Surv. Bull. 340. p. 174. 1907.
[14] J. W. Finch, *op. cit.*

of the ores might have been caused by minerals in the sediments, and was not necessarily due to the proximity of the plant remains.

In sediments containing organic material, we would expect to find hydrogen sulphide. This is true of the "Red Beds," [15] and many wells and springs in these rocks contain this compound. This gas would be retained in the rocks and would precipitate sulphides from sulphate solutions by a simple chemical metathesis. It is not known by the writer whether sufficient hydrogen sulphide could be derived from organic remains to account for the extent of these deposits, but the presence of this compound in the waters of the "Red Beds" indicates that such precipitation must have taken place to some degree at least.

Another possible mode of precipitation is by the action of kaolin on the metallic solutions. It has been shown experimentally [16] that kaolin can precipitate copper as the basic sulphate from solutions of cupric sulphate. This precipitation is due largely to the chemical action of the natural silicic acids contained in the kaolin, and colloidal adsorption plays only a minor part. In the case of the ore-bearing sediments of Nova Scotia and New Brunswick, it will be remembered that they contain considerable amounts of the feldspars, greatly altered to kaolin. This kaolin would no doubt cause some precipitation of the basic sulphate. In order to convert this to chalcocite, there would have to be present in the sediment some reducing agent, but the writer can suggest no substance that would bring about such reduction.

The concretionary and nodular structure of some of the ores may perhaps best be explained by surface tension.[17] This force, acting inward towards a central nucleus, tends to form a spherical shape.

[15] W. Lindgren and L. C. Graton, "Ore Deposits of New Mexico," U. S. Geol. Survey Prof. Paper 68, p. 79, 1910.

[16] E. C. Sullivan, "The Interaction between Minerals and Water Solutions . . . etc.," U. S. Geol. Survey Bull. 312, 1907.

[17] H. C. Boydell, "The Rôle of Colloidal Solutions in the Formation of Mineral Deposits," *Inst. of Min.* and *Met.*, vol. 34, pp. 192–193, 1924–1925.

SUMMARY.

In all probability these deposits of earlier pyrite and later chalcocite were formed by descending meteoric waters containing metals in solution principally as the sulphate, derived by weathering and oxidation from older rocks or deposits.

These solutions then seeped down to underlying sediments and precipitated out their metals as the sulphides by: (1) the reducing action of the decomposition products of wood; (2) hydrogen sulphide which was retained in the rocks after the decomposition of organic remains; (3) the action of natural silicic acids derived from kaolin contained in the sediments.

ACKNOWLEDGMENT.

In conclusion the writer wishes to acknowledge his great indebtedness to Dr. Waldemar Lindgren for his many helpful suggestions and for reading this paper.

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EDITORIAL

MINERAL EXPLORATION[1]

In discussing the subject of mineral exploration, one is tempted to resort to reminiscence. I could tell of many missed opportunities, but I propose rather to outline certain changes in the methods and conditions of exploration which present new problems to the mineral explorers of today. Our subject might appropriately be called "The Passing of the Old Time Prospector."

The first question that presents itself is whether the job of mineral exploration is not already pretty well finished. The current market surplus of most minerals and the present overcapacity for production (with their attendant financial troubles) naturally raise the question whether the accumulation of reserves has not gone far enough for the present, and whether further exploration should be left to some future time when consumption shall have caught up. Unquestionably we have gone far in the conquest of our physical environment, and the fear of shortage of minerals is less than formerly. For the time being there is no great need of further supplies for the world as a whole of many of the great essential minerals, coal, oil, copper, zinc, silver and others. For a few minerals, such as gold and lead, the known future world supplies are not yet large enough. For all minerals the distribution is so unequal among the nations that exploration will continue in deficient areas in the attempt to make nations self-supporting. The United States, as prolific in minerals as it is, still lacks adequate quantities of antimony, manganese, nickel, tin, asbestos, bauxite, natural nitrates, platinum, potash, mercury, tungsten, barite, china clay, fluorspar, graphite, magnesite, mica, and pyrite, and the search for these minerals will go on. Also, for all minerals, the distribution of reserves

[1] Adapted from an address to the Brookings Institution and American Institute of Mining and Metallurgical Engineers, Washington, D. C., February 9, 1931.

among the larger industrial units is so unequal that exploration will continue to strengthen the position of weaker units, more or less regardless of the adequacy of world or national supplies.

But there are other reasons why the quest for reserves will go on, even for minerals already known in large quantities. The rapid rise in mineral consumption during the past few decades requires proportional increase in reserves to maintain the desired life of the mineral industries. To illustrate: if twenty years ago there were twenty units of reserve behind one unit of production and the present production is now three units (not an unusual increase), the reserve necessary to maintain the ratio would be sixty units. It does not do simply to find each year an amount equal to the production for that year, a policy which has been more or less followed by some mining companies. As a matter of fact, present economic conditions require even larger reserve ratios than in the past. As commercial units grow in size, they can and must take a long-range view of the future. The chances of supplying future deficiencies in requirements by purchase of products in the open market are lessened about in proportion to the increase in requirements. It may be easy enough to shop around for a small supply, but sources of large supply are few and usually closely controlled. It will not do to be hazy about reserves for the latter parts of amortization periods—they must be known to be sufficient to last out such periods. Banking interests now figure more largely in the mineral industries, and their accounting insists on definite future supplies large enough to cover the full period of amortization and loans. Probabilities are not accepted at face value, as has been clearly demonstrated in many recent merger negotiations.

This situation may in part explain some of the apparently contradictory trends in exploration to be noted at the present time. Mineral industries which are staggering under a load of over-production and over-capacity view with alarm any suggestion of exploration which will increase current over-production, but nevertheless are showing an undercurrent of activity in acquiring still further supplies for the distant future. In iron ore, for instance, present over-capacity for production is a serious em-

barrassment, but not in twenty-five years has there been anything like the present attention to reserve for the far future, because of the necessity of making sure of the protection of huge capital investments to be amortized over long periods. Oil consumption has multiplied about eight times since the opening of the century. To maintain the same life as could have been predicted in 1900 the reserves must now be eight times as great. In the meantime the vast increase in capital investment based on oil is requiring a longer life and a greater certainty of life than was formerly thought necessary.

Viewed in this perspective, the huge reserves of some of our minerals are not so excessive as might be imagined from a consideration of current difficulties of curtailing production and financing. The fact is that we have not yet learned adequately to administer the large reserves necessary under modern conditions, and for some of the industries, like oil and iron, the conditions of ownership, leasing and political regulation are badly maladjusted to the economic necessity of insuring the requisite future supplies.

We may conclude, therefore, that, notwithstanding the fact that present mineral reserves are the largest in history, exploration will continue in large volume with constantly more selective stress on particular minerals in particular countries.

A new condition which confronts the explorer of today is the better geographical definition of potentially mineralized fields. The world is becoming pretty well known geographically and geologically, and there remain only limited regions where miscellaneous mineral discoveries are awaiting the first comer. The experienced explorer for any particular mineral now knows what geographic and geologic regions offer the best chances. He will not look for oil in pre-Cambrian rocks nor in crystalline-metamorphic rocks nor in igneous rocks; he will attempt to follow certain favorable horizons, the general trend and distribution of which are more or less known; he will test deep horizons in known fields. Enough is known, for instance, about South America to mark the broad zone following the entire east slope

of the Andes as a place of potential discovery, or the great belt of Tertiary folding extending from Rumania through Russia into Mesopotamia. Explorations for iron ore will favor the late pre-Cambrian sedimentary horizons in Brazil, South America, Australia, and India. Exploration for copper, lead, zinc or gold immediately suggests certain geologic and geographic limitations. There will be geographic changes in mineral fields, but for the most part these are likely to be in broadly predictable directions.

In considering the geographic limitations of exploration we should not overlook the scale of modern mineral requirements, to supply which only the really large mineral deposits count. While many small deposits are likely to be found in unexpected places on the surface, the chances of finding really great districts which will figure largely in meeting modern demands are small, because exploration has already gone far enough, even in remote places, to eliminate most of the chances for finding anything really large. Even if found, they may not greatly affect the trends of the mineral industry for a long time, because of remoteness or because other large undeveloped districts are already known which will take precedence in development.

In proportion as geographic possibilities are limited, exploration will increase in intensity in the known mineral regions. In these regions the easy things have been found. Future discoveries will be made in covered areas or at greater depths. This will require the more intensive use of geological, geophysical and technological methods. Better scientific training will be necessary. More expense will be involved. Chance discovery by untrained men will continue, but the burden is being rapidly shifted to men trained to meet the new conditions. The popular skepticism against science in exploration still exists, but reliance of the great mineral industries on trained explorers is rapidly becoming the normal condition.

Another new factor in exploration is the concentration of commercial control of minerals in fewer hands than formerly. Most of the world's mineral business is done today by very few large organizations. There are world monopolies in several minerals,

and near-monopolies in others. The integration of the industry is proceeding rapidly in all countries, and steps in the opposite direction are extremely rare. A very large part of present-day exploration is initiated, guided, and supported by the large companies, in sharp contrast to the old days of individual prospecting. Even where a discovery is made by the individual prospector, the exploration and development soon come under control of the larger companies with the necessary funds and marketing facilities. The new methods of exploration are expensive, and for this reason alone exploration will gravitate more and more to the larger companies. Such companies also are in a position to overcome the political barriers set up against alien exploration in a good many parts of the world. I need mention only the common method of exploration through the acquirement of large concessions, which is the only way the job can be done in some countries, to bring to your mind the difficulties under which the individual prospector labors.

Finally, the explorer of today faces new political controls which must greatly influence his course. In nearly all parts of the world governments are tightening their control of mineral resources, in a great variety of ways. Some of the political measures involve support of exploration through direct contribution, through bounties, or indirectly through tariffs and embargoes and other restrictive measures designed to foster domestic industries. For the most part, however, the new political measures are restrictive in their effect on exploration. Even in our own country the right of free entry on government lands is no longer general. Certain lands have been withdrawn entirely, others are subject to exploration only under definite restrictions. When the explorer starts abroad he will find most of the best exploring ground bristling with restrictions or outright prohibitions against foreign exploration. The "closed door" for mineral exploration in one form or another is the rule rather than the exception around the world. The door may often be opened, but this requires political negotiation and usually large capital; for some countries only very large alien companies have been in a

position to arrange an entrance. The explorer of today contemplating activities in any foreign country will do well to study all the political complications before starting. In almost every direction he will run afoul of new political measures designed to secure national political control.

The net effect of the new political control is to make exploration less orderly and efficient from a world standpoint than it would otherwise be. Unnecessary exploration is locally encouraged for national reasons even when world supplies are already excessive. By restricting exploration to own nationals, activities which may be highly necessary and desirable from the world standpoint may be held back by lack of local capital or by lack of necessary knowledge and skill. In short, freedom of private initiative to adapt exploration to world mineral requirements is to some extent sacrificed to political design, which is usually conceived in a spirit of strict nationalism, without adequate consideration or knowledge of the broader aspects of the problem.

With conditions as they are, what, then, is the best preparation for the modern explorer?—a question often asked of those of us engaged in teaching. The ideal explorer should be a good geologist, trained in a dozen special fields, a geophysicist, a technologist of wide attainments, a member of a powerful commercial organization, a student of political trends, and a diplomatist. Obviously no such person exists nor is he likely to exist. All the necessary qualities are available only in groups of specialists. Coördinated group attack seems to be the key to the problem. This is already the tendency, as an inevitable consequence of the new trends in the exploration field. Some of the glamor of individual prospecting in remote new countries will be lost, but a new scientific interest is introduced. Geographic frontiers are giving away to the frontiers of science. Some of the great successes of coördinated scientific efforts in recent years have afforded thrills to the participants which ought to satisfy the most imaginative.

C. K. LEITH.

DISCUSSION AND COMMUNICATIONS

THE STABILITY RELATIONS OF GOETHITE AND HEMATITE.

G. TUNELL AND E. POSNJAK.

IN an article entitled "Hydrothermal Oxidation and Leaching Experiments; Their Bearing on the Origin of Lake Superior Hematite-Limonite Ores" J. W. Gruner describes certain interesting experiments on the chemical behavior of ferric oxide hydrate and states a conclusion based on these experiments as follows:[1]

> The stability of limonite in the presence of water was tested at 250° C. and 300° C. in sealed thick-walled pyrex tubes. At 250° C. limonite showed no change. At 300° C. it was found that limonite in the tube above the water turned a brilliant red, whereas the limonite under water remained unchanged. The time of the experiment was 21 days. On analysis it was found that the whole sample in the tube contained 5.95 per cent. volatile matter after drying at 105° C., and the ignition loss of the original material after drying at 105° C. was 12.13 per cent. This very peculiar behavior of ferric hydroxide at these temperatures will be investigated further. It is probable, however, that as Van Bemmelen pointed out long ago, limonite is stable in the presence of water and under corresponding pressures at temperatures which approach 300° C.[2]

We believe Gruner's conclusion to be erroneous on the basis of the following experimental work.

[1] ECON. GEOL., vol. 25, p. 715, 1930.

[2] The use of the term "limonite" by Gruner in a detailed physico-chemical and geological investigation of iron ores is open to criticism, since at the present time this term is generally used by mining geologists and members of the U. S. Geological Survey and of the Geophysical Laboratory to denote unidentified ferric precipitates including hematite, goethite, lepidocrocite, jarosite, etc., and has sometimes been used by members of the Geophysical Laboratory to denote fine-grained aggregates of ferric oxide monohydrate (goethite). There is no mineral species, limonite; the formulas given under this name in mineralogies are erroneous. In the experiments described in the quotation the "limonite" used appears to have been somewhat impure ferric oxide monohydrate, as the ignition loss of the "limonite" dried at 105° C. was stated to be 12.13 per cent. The percentage of water in ferric oxide monohydrate is 10.14.

1. In the investigation of the ternary system, Fe_2O_3–SO_3–H_2O,[3] the transition temperature of $Fe_2O_3 \cdot H_2O$ (goethite) to Fe_2O_3 (hematite) in the binary system, Fe_2O_3–H_2O, considered as a limit in the ternary system, lies near 130° C. By the transition temperature of $Fe_2O_3 \cdot H_2O$ (goethite) to Fe_2O_3 (hematite) in the binary system, Fe_2O_3–H_2O, is meant the invariant point at which $Fe_2O_3 \cdot H_2O$ (goethite), Fe_2O_3 (hematite), solution, and vapor are in equilibrium. From 200° with decreasing temperature the field of hematite narrows rapidly and has an apex in the neighborhood of 130°; from 75° with increasing temperature the field of goethite narrows and has an apex in the neighborhood of 140°. Therefore it must be concluded that goethite is unstable at temperatures not much above 140°. Thus the temperature 130° was given in the published report as the approximate location of the transition temperature of $Fe_2O_3 \cdot H_2O$ (goethite) to Fe_2O_3 (hematite) in the binary system, Fe_2O_3–H_2O. To fix brackets for the transition point is very difficult, but the narrowing of the $Fe_2O_3 \cdot H_2O$ (goethite) and Fe_2O_3 (hematite) fields in the ternary system shows that the transition temperature in the binary system cannot be very far from 130°.

2. In an unpublished experiment made by E. Posnjak at the boiling temperature of an about 1/10 normal HCl solution, that is, at practically 100°, natural goethite was converted into hematite in the course of a few weeks. The identifications were accomplished by means of the X-ray diffraction patterns of the original material and the product resulting from it in the experiment. The conversion of goethite into hematite in this HCl solution is not in conflict with the transition temperature in the binary system, Fe_2O_3–H_2O, obtained as a limit in the system, Fe_2O_3–SO_3–H_2O, since the hematite and goethite fields may overlap more in the system, Fe_2O_3–HCl–H_2O, than in the system, Fe_2O_3–SO_3–H_2O. The relations of the hematite and goethite fields in the system, Fe_2O_3–HCl–H_2O, are illustrated schematically in perspective in Fig. 1. This figure may be compared with the figure depicting the model for the system, Fe_2O_3–SO_3–H_2O, published by Posnjak and

[3] E. Posnjak and H. E. Merwin, The System, Fe_2O_3–SO_3–H_2O, *Jour. Amer. Chem. Soc.*, 44, p. 1965, 1922.

Merwin.[4] In the published figure depicting the model for the system, Fe_2O_3–SO_3–H_2O, the fields of hematite and goethite are represented as meeting at a point and not overlapping at all, but the possibility of a small overlap was not disproved experimentally. Thus, if complete experimental data were available for the system, Fe_2O_3–HCl–H_2O, it is believed that the transition tem-

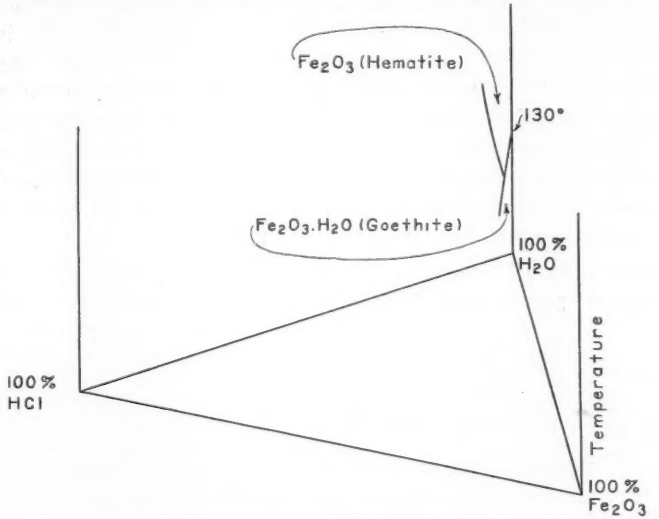

FIG. 1. Schematic illustration, in perspective, of relations of goethite and hematite fields in the system, Fe_2O_3–HCl–H_2O.

perature in the binary system, Fe_2O_3–H_2O, obtained as a limit in the system, Fe_2O_3–HCl–H_2O, would be the same as that obtained as a limit in the system, Fe_2O_3–SO_3–H_2O.

3. In experiments reported some time ago [5] in which samples of well crystallized and also optically "amorphous" ferric oxide monohydrate (goethite)[6] were dehydrated to constant weight at

[4] *Op. cit.*, p. 1993.

[5] E. Posnjak and H. E. Merwin, The Hydrated Ferric Oxides, *Amer. Jour. Sci.*, 47, p. 311, 1919.

[6] The natural optically "amorphous" material was proved to be essentially ferric

successively higher temperatures, it was found that complete decomposition occurred below 200° C. in several cases. It should be realized that the lowest temperatures at which experimental points were plotted on the higher temperature branches of the curves [7] are not necessarily close to the decomposition temperature; in all cases, if the experiments could have been extended over a longer period of time the higher temperature branch could have been prolonged backward to somewhat lower temperatures. With increasing temperature the hiatus in each curve between the lower temperature branch and the higher temperature branch begins where the substance begins to decompose, the decomposition being accompanied by the color change from yellow to red: during decomposition, of course, constancy of weight was not obtained and therefore no experimental points were plotted. In the paper on "The Hydrated Ferric Oxides" it is stated that:

> Most of the time required by the dehydration experiments was consumed for the decomposition of the substance. Before decomposition begins and after it is practically completed, the substance comes very rapidly to constancy under the conditions of experiment. Decomposition proceeds, however, at an exceedingly slow rate at the temperature at which it is first discovered and it was necessary to raise the temperature considerably to dehydrate the substance within a reasonable period.

The vertical dotted line connecting the upper and lower branches of the curve is drawn in each case at the point at which continuous loss of water was observed, which, however, does not represent the exact decomposition temperature. "In a comparative determination of the decomposition temperatures of several specimens, other factors, such as physical structure, size of grains, etc., will also prove of considerable influence."

These experiments made in open weighing glasses do not serve

oxide monohydrate in the work published by Posnjak and Merwin in 1919; proof has subsequently been obtained by X-ray powder diffraction photographs that these optically isotropic aggregates of analyzed natural material are goethite. The analyses are Nos. 19 and 23 of Table III, *Amer. Jour. Sci.*, 47, p. 318, 1919. (The molecular ratio of Fe_2O_3 to *total* H_2O of each of the samples 19 and 23 is given in Table III; the molecular ratio of Fe_2O_3 to *combined* water of each of the samples 19 and 23 is given in Table V, p. 332.)

[7] *Idem*, pp. 329 and 330.

to locate the transition temperature in the binary system, Fe_2O_3–H_2O. If the dehydration were quickly reversible the decomposition would have taken place at temperatures below the transition temperature; in some of the experiments decomposition began near 130° but in several cases, owing to the slow reaction velocity, decomposition did not commence until temperatures considerably above the transition temperature were reached. Thus the data obtained in these experiments do not conflict in any way with the transition temperature in the binary system, Fe_2O_3–H_2O, obtained as a limit in the ternary system, Fe_2O_3–SO_3–H_2O.

Slowness of the rate of decomposition may easily give rise to the idea that equilibrium has been attained, whereas in reality the substance is unstable. Gruner's experiments do not furnish any evidence of true stability and on the basis of the experimental results of Posnjak and Merwin cited above it seems only too probable that the "stability of limonite . . . in the presence of water and under corresponding pressures at temperatures which approach 300° C." is only its slow rate of decomposition.

In the application of physical chemistry to geological problems great care must be exercised to discriminate between the ideas of inertness and stability.[8] P. Niggli has stated that neither the existence fields (Existenzfelder) nor the formation fields (Bildungsfelder) are necessarily identical with the stability fields (Stabilitätsfelder).[9] (A field is a certain range of temperatures, pressures, and concentrations.) The existence fields are dependent upon the reaction velocities until equilibrium is reached under the given external conditions, after which the existence fields cease changing (until the external conditions are altered). In other words, the existence fields may vary with the time whereas the stability fields do not. Both the reaction velocities and the equilibria toward which the reactions tend should therefore be taken into account, since the presence of numerous minerals ob-

[8] G. N. Lewis and M. Randall stress the necessity for making this distinction in work in thermodynamic chemistry. "Thermodynamics and the Free Energy of Chemical Substances," p. 18. McGraw-Hill Book Company, New York, 1923.

[9] Lehrbuch der Mineralogie, p. 326, Gebrüder Borntraeger, Berlin, 1920. Lehrbuch der Mineralogie. I. Allgemeine Mineralogie, Zweite Auflage, 1924, p. 523.

served by the geologist and mineralogist in various deposits depends upon the slow reaction velocities, equilibria not having been reached in some of the reactions. This statement of course in no way detracts from the importance of knowing the equilibria toward which the reactions are tending even in the cases in which equilibria are not reached in some of the reactions.[10] The geological occurrences of hematite and goethite are cases in which the distinction between inertness and stability must be clearly visioned if the occurrences are to be understood: in many places (for example, at Tyrone, New Mexico, and Morenci, Arizona) the two minerals persist together at the surface after long exposure to weathering under conditions in which one of them is really unstable.

The physico-chemical properties of hematite and goethite are radically different and they are stable at different concentrations and temperatures (except in certain solutions of particular concentrations, that is, along certain boundary curves). Only those conditions may be assumed and those reactions invoked to explain the origin of the Lake Superior hematite deposits which are known or demonstrated to produce hematite and not goethite. It is surprising that in Gruner's physico-chemical investigation intended to throw light on the origin of these deposits, no evidence, except the color, is given of an attempt to identify the oxidation products in any experiment as hematite or goethite. In materials produced in a variety of experiments in the laboratory, color is quite unreliable as a criterion for differentiating between these two minerals (color may be used cautiously in routine examination of natural products produced by similar reactions in a limited field area after careful standardization by means of other properties measured quantitatively). Of course, determination is difficult or even impossible when only a very thin film of oxidation product is produced in an experiment, but even with much less than the 50 milligrams of material which was available in one of Gruner's experiments the "reddish brown scaly hydroxide" could have been determined as hematite, goethite, or lepidocrocite, either by

[10] In fact, knowledge of the stability fields alone tells us something about the possible reactions by eliminating others as thermodynamically impossible.

the X-ray powder diffraction method or by measurement of its refractive indices by the immersion method.

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POLISHED THIN SECTIONS OF ORE AND ROCK.

Sir: In Number 3, May 1930, of ECONOMIC GEOLOGY, J. D. H. Donnay published an article under the heading "Thinned Polished Sections."

The best preparation of material for studying ore and rock in transmitted and reflected light is either the polishing of a thin section (polished thin section) or the thinning of a polished specimen (thinned polished section).

Mr. Donnay on the grounds exposed in his article prefers the latter method. We have been preparing polished thin sections for a considerable time in this laboratory and after experimenting in every conceivable direction have arrived at the conclusion that the quickest and the safest way to achieve our purpose is to polish a thin section. Briefly our procedure is as follows:

The flat side of the sawed-off specimen is ground first with coarse carborundum powder, then with fine emery powder, and last of all with the very finest emery powder obtained in the laboratory by elutriation of the commercial article. This last stage of grinding is of the utmost importance and should be done on a very smooth plate-glass surface. This ground surface is now glued (with Canada balsam of a special consistency) on the mounting-glass, the corners and edges of which have been rounded off. The thin section is now finished by the ordinary procedure until the slice has a little more than standard thickness, when the final grinding with the same special powder mentioned above is resorted to. This is essential to accomplish a quick and efficient polishing without reducing too much the thickness of the section.

This polishing is done first on the revolving disk lined with madapolam cotton and finished on billiard cloth with the finest alundum, and takes only 3 to 10 minutes depending upon the hardness of the minerals.

Mr. Donnay discusses the following disadvantages of polished thin sections which we have found not to outweigh its advantages.

The beveling of the edges and the rounding of the corners of the mounting-glass can be done without any difficulty before starting making the thin section, and will not take more than a fraction of a minute.

We have devised a very simple holder in which the mounting-glass is clamped. With this holder it is just as easy to polish a thin section as a chunk of ore if the precautions mentioned above have been taken. The danger of ruining the thin section by polishing is very small; of the last thirty polished thin sections which we made not one was lost by polishing.

The drawback of the tarnishing of polished sections is common to all polished surfaces. Some of our polished thin sections have been repolished a dozen times without any damage. To rub off the tarnish, the slightest polishing with the finest powder on the softest cloth is generally sufficient. Moreover it is always possible to cover the polished section afterwards with a thin cover glass to protect it from tarnishing if one accepts the drawback attached to it (no etching tests possible and use of the highest magnifications precluded). Mr. Donnay's objection to the polishing of thin slices, on the ground that they cannot stand the rough treatment of polishing, does not hold in our opinion provided the precautions which we have described are taken. The accompanying photographs demonstrate that thin sections are sturdy enough to stand careful polishing.

The drawbacks which in our opinion are attached to Mr. Donnay's method are: the delicate operation of transferring the thinned polished section with a thickness of .03 mm. onto a cover glass, the limit of possible magnifications, and the overstrain in the superficial layer, which tends to make the transfer of the section an even more delicate operation.

The accompanying photographs are intended to show how, by this procedure, preparations can be made which both for transmitted and reflected light give very good results.

The polishing is as good as can be expected (see fig. 1), an

even standard thickness of the slice is obtained, and these polished thin sections can be made in little more time (3 to 10 minutes) than is required for the ordinary thin section and with a minimum risk of loss.

In addition to the advantages that will accrue from the use of the polished thin sections to the student of ore deposits, we believe

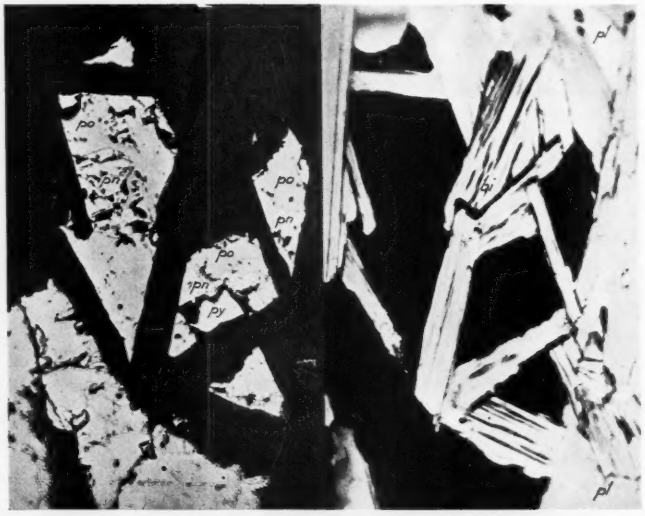

FIG. 1 (left). Evje, Norway. Reflected light. ×90. *po*, pyrrhotite; *pn*, pentlandite; *py*, pyrite.

FIG. 2 (right). Same as Fig. 1. Transmitted light. *bi*, biotite; *pl*, plagioclase.

that the petrographer also will derive considerable benefit from these slides, which afford a much closer study of the relation between the different silicate minerals owing to the more accurate details of the boundaries.

Our thanks are due to Dr. Kruizinga for assistance in making the photographs with transmitted light.

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DELFT, HOLLAND.

REVIEWS

The Coal Fields of the United States. General Introduction, by MARIUS R. CAMPBELL. Ohio, by J. A. BOWNOCKER. Pp. 101, Pls. IX, Figs. 49. U. S. Geol. Surv., Prof. Paper 100, Washington, 1929 (Dec., 1930).

In 1905 the Geological Survey began a systematic study of the coal lands of the United States with the object of securing a proper classification and valuation of its coal lands and an accurate estimate of its coal resources. The report under review is one of the results of this investigation. The general introduction by Campbell deals with the coals of the country as a whole, their distribution, classification, composition, production and reserves. The larger portion of the report, prepared by the late Dr. Bownocker, for many years State Geologist of Ohio, and his associates, covers in detail the coal fields of Ohio. The report contains a mass of valuable information clearly presented for the reader interested in coals in general or in a detailed description of Ohio's deposits. The text is splendidly illustrated by maps and sections, including a map of the coal fields of the United States, in two sections, on a scale of about 28.5 miles to the inch and showing the distribution of the different ranks of coal throughout the country. There is also a map of Ohio and there are several of the individual coal fields of that state.

In classifying the coals no attempt has been made to employ the more elaborate but still imperfect classifications suggested by various writers who have striven to devise some means whereby the consumer may obtain a more definite idea than that conveyed by the old terms in use, of the nature and value of the coal he is using. The terms, lignite, subbituminous, bituminous, semibituminous, semianthracite and anthracite, as used by the Geological Survey for the various ranks, are the ones employed and a concise interpretation of the terms is given by Campbell. He points out the unfortunate use of the term semibituminous in describing coal of higher rank than bituminous coal. In the classification of coal-bearing areas the divisions of coal district, field, region, and province, in general use by the Survey, are employed in the report.

The estimates of the coal resources of the United States and the world presented in the paper are taken from the report of the International Geological Congress, Canada, 1913. It is no doubt disappointing to many readers of the report that Campbell, a recognized authority on coal, has not given us the benefit of more recent estimates, since those for several countries have changed somewhat in sixteen years. The degree

of dominance of the United States in the world's resources (51 per cent. of the total) has probably, however, changed but little in that time. The production of 23,000,000,000 tons a decade for the country by the end of 2055 as postulated by Parker some years ago is considered by Campbell as too low in view of the increase in coal production in recent years. In spite of the depressed state of the coal industry, due to the use of substitutes and to other causes, the production curve has been climbing steadily upward. According to Parker's estimate the curve will begin to flatten rapidly about the end of the present century.

E. S. MOORE.

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Field Geology. By F. H. LAHEE. 3d Ed. Pp. xxxi + 789, figs. 538. McGraw-Hill Book Co., New York, 1931. Price, $5.00.

This valuable reference work has been brought up to date by the revision of many parts of the text. The new material consists principally of three chapters dealing respectively with airplane mapping, subsurface geological surveying, and geophysical surveying. Brief descriptions are given of the methods, difficulties and geologic applications of airplane surveying, of the structural interpretation of drill cores, and of the preparation of drill cuttings for examination for microfossils and heavy minerals. The problem of crooked holes and their effect upon structure contouring, the use of geothermal data in problems of geologic structure, and the principles of four geophysical methods, the gravimetric, magnetometric, seismic and electric, are also discussed.

The chapter dealing with instrumental methods in field mapping has additions dealing with the care and adjustment of the telescopic alidade, with the use of the Beaman arc and the Stebinger gradienter drum, with the correction of rod elevation for curvature and refraction, and with the correction for atmospheric pressure and temperature variations in the use of the aneroid barometer.

The bibliography includes a large proportion of citations of articles published since 1923, the date of the second edition.

H. R. WANLESS.

UNIVERSITY OF ILLINOIS,
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Systematic Crystallography: An Essay on Crystal Description, Classification and Identification. By T. V. BARKER. Pp. xi + 115, Illus. 76, and 2 stereographic nets. Thos. Murby & Co., London, 1930. Price, 7 s 6 d.

This little book seeks to present the "principles of a systematic crystallography by which the surface of a crystal may be (1) unambiguously

described in terms of a standard set of axes and parameters derivable from the form development; (2) classified morphologically according to its angular values; and, (3) identified on any future occasion by the simple process of measurement, geometrical analysis and reference to tables." The first part of the book deals with general principles which are presented in stereographic projections, and the second part illustrates the principles by applying them to crystals of the various systems, and discussion of the results. The author's main thesis is that the present method of selecting axial constants leaves too much to the individual student and the first observer of a crystallized substance, and consequently there is no uniformity in the choice. He offers a method based upon the zonal relations of planes by which the most appropriate axes for any crystal may always be selected.

W. S. BAYLEY.

World Minerals and World Politics. By C. K. LEITH. Pp. 213. Whittlesey House, McGraw-Hill Book Co., New York, 1931. Price, $2.00.

This interesting little book analyzes the political significance of the present and potential mineral resources of countries and continents. It deals with the geography, production, and reserves of the important mineral products, and shows the political motives that lie behind the acquisition and exploitation of certain minerals, and their tendency to make for trade, war, or peace. Public control, tariffs, conservation, and relations of minerals to the prosecution, causes, and deterrents of war, are discussed.

It is an interesting and timely book well worth reading and study.

ALAN BATEMAN.

Elements of Engineering Geology. By H. RIES AND T. L. WATSON. Second edition. Pp. 411, figs. 276. John Wiley & Sons, New York, 1930 (Dec.). Price, $3.75.

This second edition is modeled after its predecessor but contains two notable additions, *i.e.* Geology of Dams and Reservoirs (20 pp.) and a summary chapter on Historical Geology (47 pp.). New references have been added to the different chapters. Otherwise the pagination and textual matter appear to be the same as in the first edition.

This compact little book should serve for short elementary courses in physical geology with emphasis on features of interest to engineering students.

BOOKS RECEIVED

Gold Deposits of Alabama and Occurrences of Copper, Pyrite, Arsenic, and Tin. By GEO. I. ADAMS. Pp. 91, figs. 6, pls. 4. Alabama Geol. Surv. Bull. 40, University, Ala., 1930. General geology and ore occurrences in some thirteen districts.

The Jharia Coal Field. By C. S. FOX. Pp. 255 + xxxviii, figs. 13, pls. 31. Geol. Survey of India, Memoirs, vol. XVI. Calcutta, 1930. A monographic report on the stratigraphy, structure, occurrence, quality and quantity of the coal.

Carte Géologique du Congo Belge. By P. FOURMARIER. Pp. 40 (12mo), map. Rev. Univ. des Mines, 1930 (2d ed.), Liége, 1930. This second edition of the large map of the Belgian Congo, in four sheets, scale 1 : 2,000,000, is accompanied by a descriptive text embodying recent data. (In French.)

Water Supply, Brazil (Forcas Hydraulicas, Trabalhos de 1928). Pp. 51, illus., contour maps. Serv. Geol. e Min. do Brasil, Bol. 51, Rio de Janeiro, 1930.

Annual Report of Director, Serv. Geol. and Min. do Brazil, 1929. By G. DE L. GASTRO. Pp. 122, chemical analyses. Rio de Janeiro, 1930.

Canada Geological Survey, Summary Report, 1929, *Pt. A* (No. 2251), Pp. 319, pls. 4, figs. 21, maps. Mining Industry, Yukon, 1929, by W. E. COCKFIELD; Taku River District and Iskut River Area, by F. A. KERR; Owen Lake Mining Camp and Mineral Deposits at Buck Flats, by A. H. LANG; Quatsino-Nimpkish Area, Vancouver Island, by H. C. GUNNING; Serpentine Belt of Coquihalla Region, Yale District, by C. E. CAIRNES; Nickel Plate Mountain, Hedley, by H. S. BOSTOCK; Mineral Developments in Salmo Map-Area, by J. F. WALKER; Clearwater Lake Area, by N. F. G. DAVIS, Deep Borings in British Columbia, by D. C. MADDOX. *Pt. C.* (No. 2250), pp. 50, fig. 1. Mineral Occurrences in Woman River District, Ont., by H. M. BANNERMAN; Obatogamau River Area, Que., by C. TOLMAN; Deep Borings in Eastern Canada, by D. C. MADDOX. Ottawa, Canada. 1930. (Jan. 1931.)

Zinc and Lead Deposits of Canada. By F. J. ALCOCK. Pp. 406, pls. 8, figs. 34. Canada Geol. Surv., Econ. Geol. Ser. 8 (No. 2229). Ottawa, 1930. Price, 75 cts. A monographic report on the mineralogy, geology, distribution, world occurrence, and statistics.

Feldspar in Pennsylvania. By R. W. STONE AND H. H. HUGHES. Pp. 63, pls. 20, figs. 6. Penn. Top. and Geol. Survey, Bull. M–13, Harrisburg, 1931. Geologic occurrence, mineralogy, description of deposits.

Outlines of Historical Geology. By CHARLES SCHUCHERT. 2d edit.

Rewritten. Pp. 348, figs. 157. John Wiley & Sons, New York, 1931. Price, $3.00. The book is largely re-written and simplified for a short course textbook. Combined with the abbreviated Physical Geology, it constitutes a new abridged shorter Textbook of Geology by Pirsson and Schuchert. It is up-to-date and readable.

Surface Water Supply of the United States, 1926. *Part III,* Ohio River Basin, pp. 332. Water Supply Paper 623, 1930. Price, 50 cts. *Part VIII,* Western Gulf of Mexico Basins, pp. 207. Water Supply Paper 628, 1930. Price, 35 cts. **1927,** Part VI, Missouri River Basin, pp. 216. Water Supply Paper 646, 1930. Price, 20 cts. *Part VII,* Lower Mississippi River Basin, pp. 98. Water Supply Paper 647, 1930. Price, 20 cts. *Part VIII,* Western Gulf of Mexico Basins, pp. 117. Water Supply Paper 648, 1930. Price, 20 cts. U. S. Geol. Survey, 1930 (Dec.).

Surface Water Supply of Hawaii, July 1, 1926 to June 30, 1927. Pp. 151. U. S. Geol. Surv. Water Supply Paper 655, 1930. Price, 25 cts.

Notes on the Geology of Upper Nizina River, Alaska. By F. H. MOFFIT. Pp. 24, map. U. S. Geol. Surv. Bull. 813–D, 1930. Price, 15 cts.

Boundaries, Areas, Geographic Centers, and Altitudes of the United States and the Several States (2d ed.). By E. M. DOUGLAS. Pp. 265, pls. 12, figs. 26. U. S. Geol. Surv. Bull. 817. Price, 50 cts.

A Graphic History of Metal Mining in Idaho. By C. P. ROSS. Pp. 9, pls. 3. U. S. Geol. Surv. Bull. 821–A, 1930. Price, 10 cts.

Bituminous Sandstone near Vernal, Utah. By E. M. SPIEKER. Pp. 24, figs. 4, pls. 3. U. S. Geol. Surv. Bull. 822–C, 1930. Price, 10 cts. General geology. Sandstones with 8 to 15 per cent bituminous matter, totalling nearly two billion tons of rock, used for paving and possible source of motor fuels.

Mineral Industry of Alaska in 1929: Administrative Report. By P. S. Smith, Pp. 109 + 11, figs. 4. U. S. Geol. Surv. Bull. 824–A, 1930. Price, 20 cts.

Fifty-First Annual Report, Director of Geological Survey, for year ending June 30, 1930. Pp. 89, map. U. S. Geol. Survey, 1930. Price, 15 cts.

Geologic History of the Yosemite Valley. By F. E. MATTHES. Pp. 137, pls. 52, figs. 38. U. S. Geol. Surv. Prof. Paper 160, 1930. Price, $1.10. Geography; early history; glacial history; the Granitic Rocks, by F. C. Calkins. A complete story of the Yosemite, beautifully illustrated.

Copies of books mentioned under "Reviews" or under our "New Book List" (see advertisement page) may be purchased through our Journal Bookshop by writing to W. S. Bayley, University of Illinois, Urbana, Ill.

SCIENTIFIC NOTES AND NEWS

J. A. Bancroft has left the service of the Anglo-American Ltd., operating in Rhodesia, and has joined the staff of the Chartered Company.

E. H. Wells, lately appointed State Geologist of New Mexico in place of C. G. Staley, resigned, will continue to act as President of the New Mexico School of Mines.

R. J. Colony, of Columbia University, New York, has been engaged in professional work in Mexico during his sabbatical vacation period.

W. Taylor Thom, of Princeton University, has recently been visiting the Western United States and giving addresses before several geological societies.

Hans Stille, of the University of Göttingen, Germany, spent the month of March in Texas and Louisiana inspecting salt domes.

T. M. Broderick, of Calumet, Michigan, lectured recently at Princeton University on "The Geology of the Lake Superior Copper Deposits."

H. Schneiderhöhn, professor of mineralogy at the University of Freiburg, Germany, and H. Stille, professor of geology at the University of Göttingen, have been appointed German representatives to the Council of the International Summer School of Geology, Princeton University. Dr. Schneiderhöhn has recently been appointed a corresponding member of the Geologiska Foreningen, Stockholm.

George W. Stose, editor of geologic maps for the U. S. Geological Survey, is co-operating with W. W. Bradley, state mineralogist of California, and O. P. Jenkins, chief geologist of the California Division of Mines, in the making of a state geologic map on the scale of 8 miles to the inch.

George R. Elliott is district engineer at Lethbridge, Alberta, for petroleum and natural gas in the Province of Alberta.

Malcolm MacLaren has left the Gold Coast and is now inspecting the mines of the Consolidated Gold Fields on the Rand.

L. T. Nel, geologist of the South Africa Geological Survey, has returned to South Africa after a visit to Germany.

The Roan Antelope Mine, Rhodesia, is now practically ready to send ore to the mill.

Torna Barrera, professor of geology at the National University, Mexico, and chief of the division on non-metallics, Institute of Geology of Mexico, is the recipient of a Guggenheim fellowship for work at Howard University.

James F. McClelland, formerly professor of mining at Yale University, and recently vice-president of the Chemical Bank and Trust Company of New York City, has been appointed vice-president of Phelps Dodge Corporation.

M. N. Short, of the U. S. Geological Survey, gave a series of lectures at Yale University, April 13 to 15, on "Microchemistry: its technique and application in determination of minerals, ores and metals." Dr. Short's Bulletin on "Microscopic Determination of Ore Minerals" is now in press.

The Emmons Memorial Fellowship in economic geology for the coming year has been awarded to Frederick S. Turneaure, who will carry on his work under the fellowship grant at Harvard University.

The Economic Geology Publishing Company is making an offer to bona fide university students of a subscription to the journal Economic Geology at a reduced rate of $3.50 per year. This is being done in order to encourage students to keep in touch with current literature and to build up their own private libraries. Any student may send in a subscription on this basis provided it is initialed by his professors. Teachers are requested to bring this notice to the attention of their classes.

The Geological Society of America will hold its next annual meeting at Tulsa, Okla., December 29–31. Short field trips are being arranged.

The Second International Congress of the History of Science and Technology, Dr. Charles Singer, President, will meet at the South Kensington Museum, London, June 29 to July 3, 1931. This Congress originated in 1928 with the Comité International d'Histoire des Sciences, and organizes a Congress every three years in co-operation with the parent body, the History of Science Society, Washington, D. C., and the Newcomen Society for the Study of the History of Engineering and Technology, London. The themes for discussion are: (1) Sciences as an Integral Part of General Historical Study; (2) Historical and Contemporary Inter-relationship of the Physical and Biological Sciences; (3) Interdependence of Pure and Applied Science. Further particulars can be obtained from the Honorary Secretary, H. W. Dickinson, The Science Museum, South Kensington, London, S. W. 7.

The recently published 20-volume index (336 pages) of ECONOMIC GEOLOGY for 1905 to 1925, compiled by J. M. Nickles, may be obtained for $3.00 from W. S. Bayley, University of Illinois, Urbana, Ill.